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TUNNEL BORING MACHINE TECHNOLOGY FOR A DEEPLY BASED MISSILE SYS--ETC(U)

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TUNNEL BORING MACHINE TECHNOLOGY FOR A DEEPLY BASED MISSILE SYSTEM

Volume II of II
State-of-the-Art Review

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Levent Ozdemir
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Colorado School of Mines
Golden, CO 80401

August 1980

Final Report

Approved for public release; distribution unlimited.

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This report consists of two volumes: Volume I, Application Feasibility, and Volume II, State-of-the-Art Review. Volume I is divided into two parts. Part 1 consists of the front matter and text pages 1-108. Part 2 consists of text pages 109-198 and the distribution list.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tunneling
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Rock Mechanics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Technical feasibility and cost studies were made for a deep-based missile (DBM) tunnel system (Mesa concept) by means of tunnel boring machines (TBMs), along with designing an egress machine for post-attack tunneling through approximately 2,500 feet of probably unstable rock to the rubble zone.

Currently, available designs of TBMs are readily adaptable for the conventional excavation in geologic environment considered suitable for DBM siting. Most, if not all, of the tunnel sections in the rocks of anticipated structure

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and strength will require support varying from simple rock bolting to concrete segments.

Current (1979) costs for similar tunnels (Chicago) vary from $600 to $800 per linear foot of tunnel, while the estimated costs for the DBM tunnels average as high as $1,600 per foot because of the greater depths, weaker rock, longer tunnels, possible remoteness geographically, and other related factors.

Two concepts for egress machines have been proposed by the Robbins and Jarva companies.

The details of use of geotechnical data are given in Appendix A and were qualitatively for estimates of support requirements and costs. The only calculation that could be made based upon available data was the assumption that squeezing ground would occur if the stress concentration at the ribs of the tunnels exceeds the unconfined compressive strength. Average conditions assumed for the tunnel calculations in the COSTUN program automatically include the effects of rock quality designation (RQD), etc.

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INTRODUCTION

The effort of this research project was carried out as a detailed feasibility study of four factors to evaluate the performance of tunnel boring machines (TBMs): (1) their capabilities, (2) limitations, (3) adaptability, and (4) cost effectiveness for (a) conventional excavation for deploying a deep-based missile system, and (b) for excavation of post-attack egress openings.

There are two missions to be performed by TBMs. The first is the excavation of 480 km of 5-meter diameter tunnels by conventional tunnel boring methods, and the second is the excavation of post-attack egress openings by modified machines. The types of TBMs required to perform these two different modes of excavation will have some elements in common and other elements which are quite different, from both a technical and a logistic point of view.

The technical aspects primarily include factors in machine design, the interaction at the rock-machine interface, control and guidance, muck handling, cutter replacement, machine repairs, evaluation of site geology, ventilation, and similar items that require skilled professionals and technicians to install, operate, and maintain.

The logistics include the management of personnel, and keeping power supplies, tools, repair parts, utilities, rock support, muck removal, and similar items available.

That is, the conventional tunneling will require long supply lines and extended continuous operation. Egress excavation will be limited to local supplies and will involve only short-term operations.

A comparison of the requirements for the two modes of excavation can be analyzed with respect to the technical and logistic environments within

which excavation operations must be carried out. In the conventional excavation, the restrictions on operations are relatively flexible. For egress excavation, the restrictions are most severe, and flexibility is practically zero. Most of the pertinent factors for conventional operation have been described in the literature (Tables 1 & 2), but some of these will be markedly different for egress operations.

Capital costs for conventional TBM excavation are of major consideration, both with respect to the cost per machine and the total project. However, for the egress tunnel boring machines (ETBMs), cost should be secondary to reliability, simplicity, and penetration rate.

A summary of the current state of the art in tunnel boring was made to serve as a basis for determining the approach to the solutions of the problems associated with deep-based missiles (DBMs). Volume II of this report covers the state of the art summary, whereas Volume I addresses the problems associated with DBM. The experimental data on single layer linear cutting described in the Bureau of Mines reports listed in the Request for Proposal (RFP) were not used here, because it has been found that when multiple successive layers of rock are removed with a linear cutter, the cutting results are different than those observed when only single depth cuts are made on one flat surface of rock.

TABLE 1

TECHNICAL REQUIREMENTS

TECHNICAL FACTORS	TBM	ETBM
1. Machine design to fit variable site conditions	Flexible for variable geological conditions	Designed for local site(s) of known geology
2. Machine construction to allow for changing conditions	Flexible for variable geological conditions	Limited flexibility, no machine changes
3. Change in design or operation to meet local conditions	Desirable for extensive excavation	Very limited for short operation
4. Changing cutters	Required for continued operation	Limited or no changes permitted
5. Repair & maintenance	As required	Limited by availability of parts and skill of personnel
6. Geological and engineering assistance	Available at all times	Not available
7. Simplified operation	Desirable but not required	Required because of limited skill of personnel
8. Ease of assembling & disassembling	Desirable but not required	Desirable but not required
9. Mobility	Desirable	Required for multiple opening excavation
10. Rate of penetration	Required to keep costs down	Required for military tactical reasons
11. Rate of advance	Required to keep costs down	Required for military tactical reasons
12. Energy requirements	Low as possible for economics	Low as possible because of limited resources
13. Operation on curves	Desirable with minimum delay	Probably not required
14. Disposal of machine	Used until amortized or worn out	Must be moved to clear egress
15. Adapt to effects of attack	Not required	Machine adapted to excavate in damaged tunnels
16. Muck removal system	Required	Required
17. Power source	Required	Required

TABLE ?

LOGISTIC REQUIREMENTS

LOGISTIC FACTORS	TBM	ETBM
1. Utilities		
a. Power	Supplied from civilian sources	Supplied from limited local sources
b. Ventilation	Conventional by vent line to outside	From local tunnel air or by drill hole to outside
c. Compressed air	Conventional pipe line	Local compressor if needed
d. Track	Conventional	Local only
e. Light	Conventional	Local source
2. Labor	Trained and skilled for operation and maintenance	Limited training and skills
3. Supplies	Conventional	Local only
4. Repair parts	Conventional	Local only
5. Management	Conventional	Local military
6. Muck disposal	Conventional - possibly by extensive conveyor system	To existing underground space, or outside through drill hole
7. Maintenance	Conventional	Local only with available parts and personnel

MACHINE CHARACTERISTICS

A review was made of the operation parameters of hard rock tunneling machines by Mellor and Hawkes (Ref. 1) to furnish basic information for operators and researchers in the field of rapid excavation. The data were taken from specifications and performance records from catalogs, published literature, information from manufacturers, and visits to projects with machines in operation in the U.S. and Europe.

The data (Figures 1 - 3) on maximum axial thrust, rated boring head power, and rated boring head torque as related to tunnel diameter for about 75 machines installations shows considerable spread, some of which is due to the machine characteristics, but most of the scatter is due to variability in geology and rock properties.

For various types of cutter-rock interfaces, there are optimum cutter pressures for efficient penetration, cutting and chipping, and these are directly related to the machine thrust and the number of cutters. The upper limits of pressure between the cutter and rock are determined by limitations on the cutter bearings and the machine power.

For typical machines, the thrust varies as the square of the tunnel diameter (Figure 1):

$$P = K_p D^2 \tag{1}$$

where

P = thrust, lb

K_p = proportionality factor, ranging from 3,000 lb/ft^2 to 11,000 lb/ft^2

D = tunnel diameter

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1. Mellor, M. and I. Hawkes, 1972, "Hard Rock Tunneling Machine Characteristics," Proc. RETC, AIME, Chicago, Illinois.

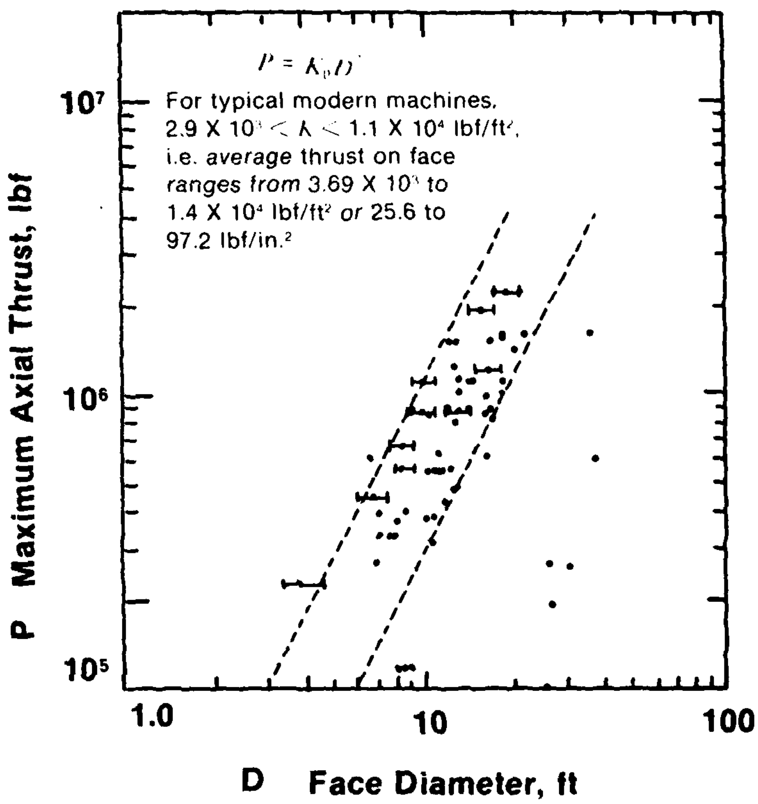

FIGURE 1 - Maximum Axial Thrust Versus Face Diameter for Hard Rock Tunneling Machines (Ref. 1)

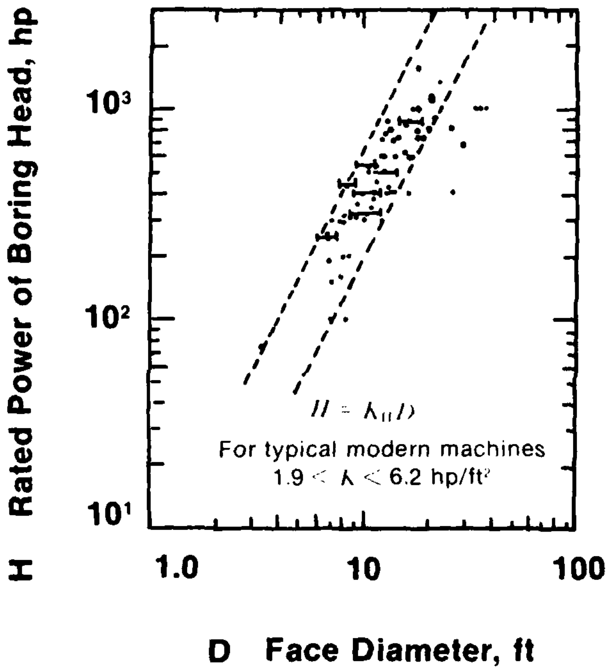

FIGURE 2 - Rated Power of Boring Head Versus Face Diameter for Hard Rock Tunneling Machines (Ref. 1)

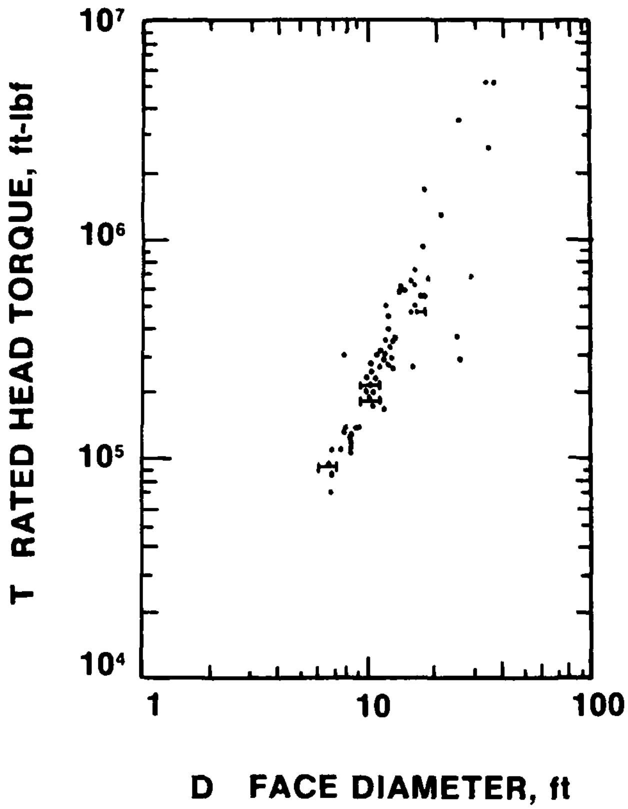

FIGURE 3 - Rated Head Torque Versus Face Diameter for Hard Rock Tunneling Machines (Ref. 1)

The thrust supported by the cutter bearings may be approximated by dividing the thrust by the number of independent cutters.

The power required is determined by the torque and rotary speed, the practical controlling factors being the power and the bearing temperature. The horsepower is also proportional to the area of the tunnel face (Figure 2):

$$H = K_H D^2 \tag{2}$$

where

H = horsepower

K_H = proportionality factor which varies from 1.9 to 6.2

The rated maximum head torque varies as (Figure 3):

$$T = K_T D^{2.3} \tag{3}$$

where

T = torque, ft-lbs

K_T = proportionality factor

For large machines, the speed is lower, which has the effect of increasing the value of the exponent in the above equations.

The specific energy or the energy required to excavate a unit volume of rock is a function and the power consumption are functions of the properties which determine the boreability of the rock. Plots of power consumption vs cutting rate and specific energy vs compressive strength show a marked scattering of data (Figures 4 & 5). The utilized head power in some cases was estimated from the installed power, the efficiency factor ranging from 40 to 60%. The data are useful only for general comparisons and not for quantitative evaluations. As might be expected, specific

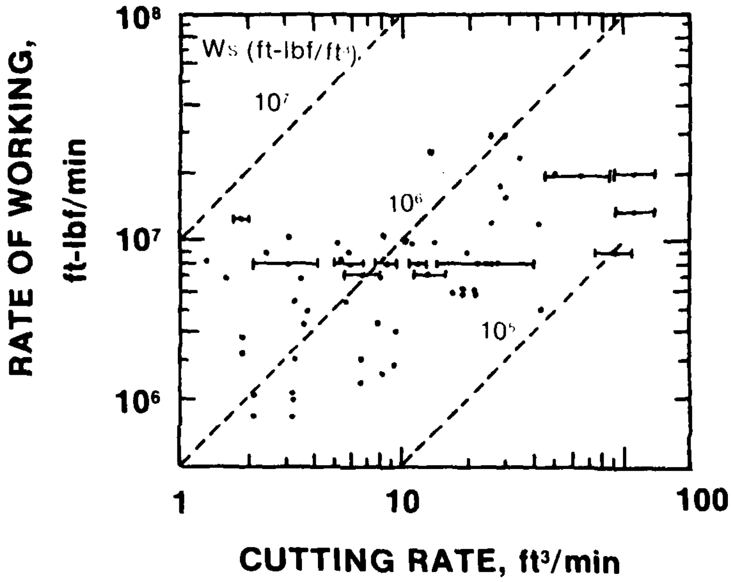

FIGURE 4 - Power Consumption Versus Cutting Rate for Hard Rock Tunneling Machines (Ref. 1)

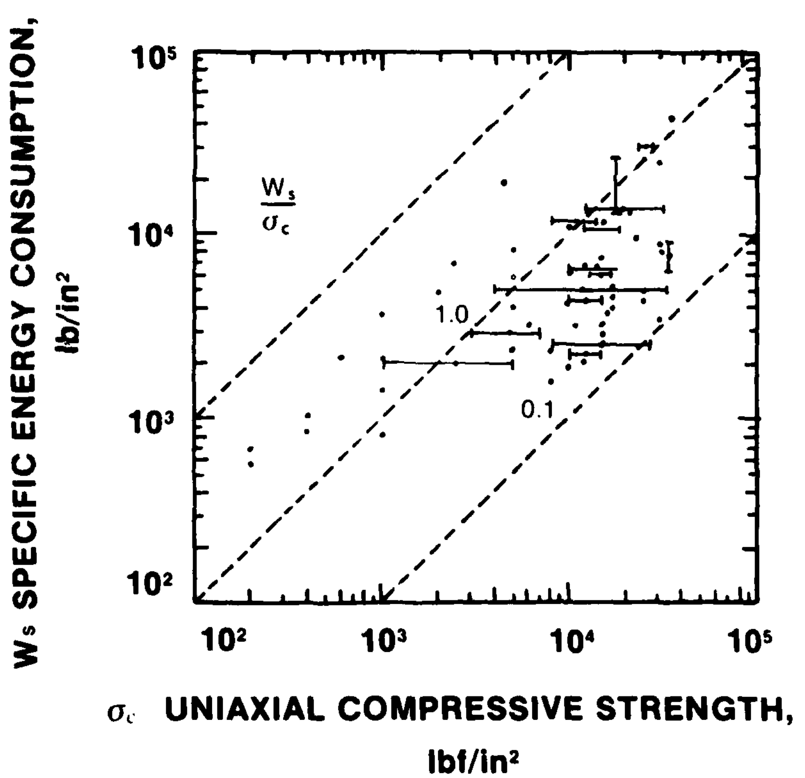

FIGURE 5 - Specific Energy Versus Compressive Strength (Ref. 1)

energy (energy per unit volume of rock excavated) does not correlate well with compressive strength (Figure 5). The results of experimental static tests show a closer correlation between specific energy and compressive strength (Figure 6), but tunneling is more efficient than static breakage, as are diamond drilling and pneumatic drilling.

At one site where boring was being carried out in limestone, the head power was measured as a function of thrust. At zero thrust, with the cutters in contact with the face, about 17% of the head power was used (Figure 7). As the thrust was increased, cutting ensued, but a substantial portion of the head power was consumed in bearing friction.

A review of the state of development and operation of both soft and hard rock tunnel boring machines was made by Muirhead and Glossop in 1968 (Ref. 2). Soft ground was defined as that which was not self-supporting and hard rock is defined as that which requires drilling and blasting or some high energy process. The range of compressive strengths (Figure 8) of typical rocks varies from 5,000 psi to 30,000 psi for sandstones and from 30,000 psi to 90,000 psi for taconites and quartzites. The types of cutters for different formations varied from picks, discs, and gear rollers for soft rock to button rollers for very hard rock (Table 3). It was noted in 1968 that hard rock tunneling was limited to rocks below a hardness of 5.0 on Mohs scale. However, hardness or compressive strength by themselves are not adequate measures of boreability (see Prediction of Field Boring Rates).

Reference 2 also summarized the characteristics of boring machines that had been used to that date (Table 4) as well as a list of

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2. Muirhead, I.R. and L.G. Glossop, January 1968, "Hard Rock Tunneling Machines," Bulletin 734, Inst. of Min. & Met., Ottowa, Canada.

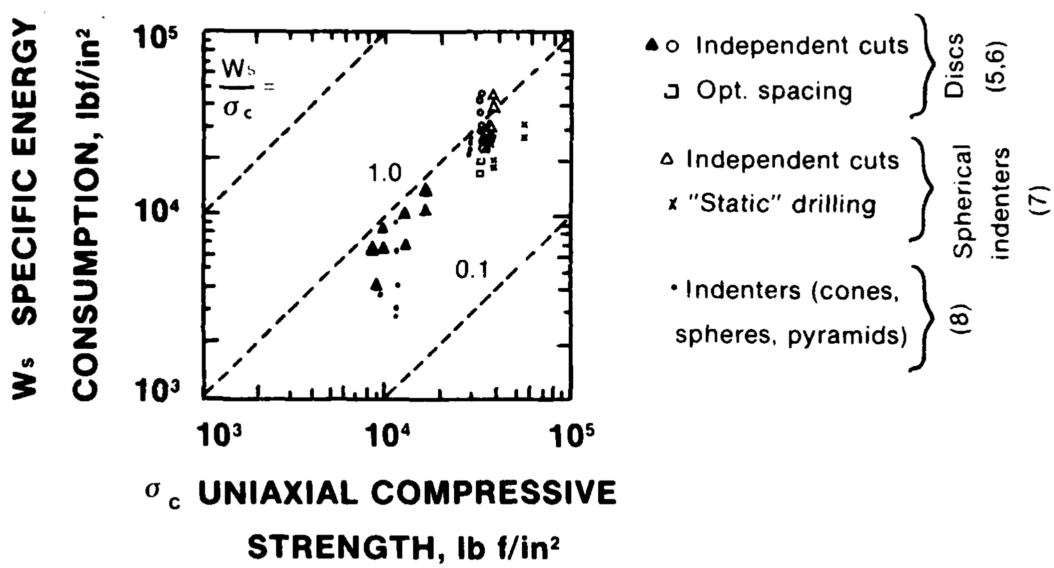

FIGURE 6 - Specific Energies Achieved in Rock Cutting Tests (Ref. 1)

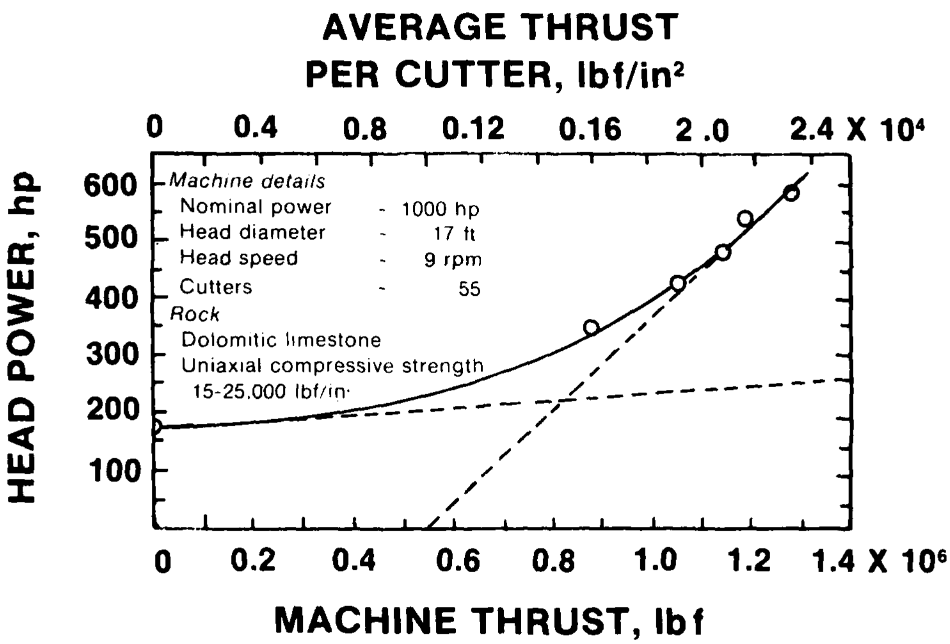

FIGURE 7 - Head Power Versus Machine Thrust (Ref. 1)

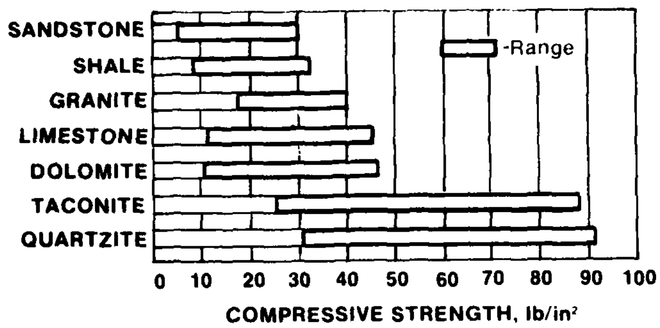

FIGURE 8 - Compressive Strength Ranges of Some Common Rock Types (Ref. 2)

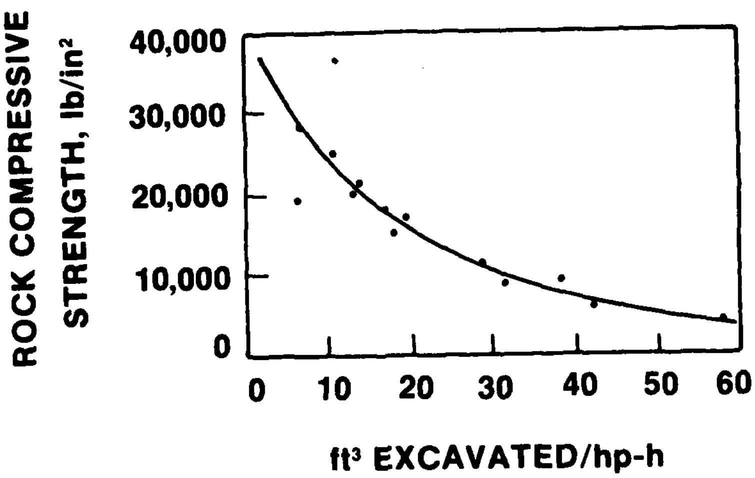

FIGURE 9 - Performance Prediction Curve

TABLE 3

TYPES OF CUTTERS USED FOR DIFFERENT FORMATIONS (Ref. 1)

	Rock Compressive Strength, lb/in^2	Typical Rocks	Cutters
Soft	6,000 (max)	Shale, clay	Picks. discs gear rollers
Medium	6,000 - 12,000	Dolomite, sand-stone, marble	Picks, discs gear rollers
Medium Hard	12,000 - 25,000	Limestone, gneiss granite	Button & disc rollers
Hard	+25,000	Diorite, quart-aite, hornblende	Button rollers

TABLE 4

TUNNELING MACHINE CHARACTERISTICS (Ref. 2)

	Total	Robbins	Hughes	Lawrence	Jarva	Calweld	Demag	Wirth	Habegger	N.C.B.	Krupp
CUTTING TOOLS											
Picks only	4	1	--	--	--	--	--	--	3	--	--
Picks & disc cutters	7	7	--	--	--	--	--	--	--	--	--
Disc cutters	24	16	--	--	--	4	2	--	--	1	1
Gear cutters	10	--	7	--	--	--	--	2	--	1	--
Button cutters	7	--	--	1	6	--	--	--	--	--	--
CUTTER DRIVE											
Hydraulic	6	--	--	1	--	4	--	--	--	1	--
Electric	46	24	7	--	6	--	2	2	3	1	1
CUTTER HEAD ROTATION											
Single direction	45	22	7	1	6	4	2	2	--	1	--
Contra rotating	7	2	--	--	--	--	--	--	3	1	1
MATERIAL HANDLING											
Buckets	33	23	7	1	--	--	--	--	--	2	--
Ploughs & buckets	14	--	--	--	6	4	2	2	--	--	--
Scraper conveyors	5	1	--	--	--	--	--	--	3	--	1
Belt conveyor through m/c	47	23	7	1	6	4	2	2	--	2	--
Scraper conveyor through m/c	5	1	--	--	--	--	--	--	3	--	1
ANCHORAGE											
Wall anchorages	43	21	7	--	6	--	2	2	3	2	--
Crawlers	1	--	--	--	--	--	--	--	--	--	1
Push rams off lining or thrust ring	7	3	--	--	--	4	--	--	--	--	--
Pilot pull-push wall	1	--	--	1	--	--	--	--	--	--	--

TABLE 5

TUNNEL DRIVAGE RATES - MACHINE AND CONVENTIONAL (Ref. 2)

Tunnel	Diameter	Length ft	Gradient %	Method of excavation	Tunnel transport	Cross-section, ft²	Average performance, ft				Maximum performance, ft				Remarks
							h	Day	Week	Month	h	Day	Week	Month	
Goss, Austria	HS	13 500	+2·4	4 hammer drills, air legs, 1 shovel loader	1 bunker train + loco	71·6	3·0	71	—	—	—	—	—	2016 (European record)	Shaly gneiss (0·27 lb/ft³ explosive)
Navajo 2, U.S.A.	HS	26 300	—	2-deck jumbo, 6 drills, conway loader	15-yd³ cars + diesel loco	395	2·8	37	180	—	—	70	300	—	Sandstone 5000–6000 lb/in² (0·69 lb/ft³)
Canyon, U.S.A.	HS	54 400	0·2	Jumbo, 6 drills, conway loader	10-yd³ cars + loco	144	3·0	71	—	—	—	—	465	—	Granite (17 000–30 000 lb/in²) 0·2 lb/ft³
Loraine mines, South Africa	HS	?	—	Air legs, hammer drills, shovel loader	4-ton cars + loco	105	3·9	86	—	—	—	97	—	2317	Rock (hard rock)
Chanrion, Switzerland	HS	32 000	0·3 –1·0	Air legs + hammer drills, shovel loader	Bunker train + battery loco	57	3·5	42	—	920	—	—	—	1100	Schist, gneiss
Navajo 1, U.S.A.	19 ft 10 in 21 ft 2 in	10 000	+0·5	Hughes Tool Beth 1 machine	10-yd³ cars + diesel loco	320	10	53	—	1160	16	171	662	—	Sandstone 5000–6000 lb/in²
St. Louis, U.S.A.	7 ft 10 in	10 000	—	Jarva Mk 8 machine	2-yd³ cars + locos	52	4·0	50	—	—	5·0	80	—	812	Limestone } Chert } 12 000–15 000 lb/in²
Philadelphia, U.S.A.	13 ft [illegible]	1 650	—	Jarva Mk 14 machine	?	145	4·4	20*	—	—	8·3	29*	—	262	Limestone } Hornblende } 6000–25 000 lb/in² *1 shift
St Louis, U.S.A.	10 ft 6 in	4 [illegible]		Jarva Mk 14 machine	?	91	3·7	—	—	—	—	55	—	—	Limestone 12 000–19 000 lb/in²
Chur, Switzerland	11 ft 6 in	[illegible]	[illegible]	[illegible]	Bunker cars + loco	103	4·0	—	1201†	—	6·0	—	—	—	Shale } Quartz } 14 000–21 000 lb/in² †2 shifts per day
Stuttgart, Germany	7 ft	4 500	—	Demag TVM 19-23 H machine	?	38	5·3	85	—	—	—	—	—	—	Limestone 29 000 lb/in²
Freiberg, Switzerland	8 ft [illegible]	[illegible]		Robbins 81-113	Cars + loco	57	10	—	—	—	—	—	—	—	Sandstone
Blanco, U.S.A.	9 ft 11 in [illegible]	41 [illegible]		Robbins 104-[illegible]	Cars + loco	80	11	[illegible]	—	3 300	—	375	1744	6711	Shale
Oso, U.S.A.	10 ft 7 in 9 ft 11 in – 10 ft 7 in	26 400		Robbins 101-121A	Cars + loco	80	14	—	—	—	—	419	1305	6841 (World record)	Shale
Azotea, U.S.A.	12 ft 4 in – 13 ft 3 in	65 000		Robbins 121	Cars ([illegible] yd³) + loco	—	7·[illegible]	150	—	—	—	241	10[illegible]	—	Sandstone } Shale } [illegible] lb/in²
Tasmania	16 ft 1 in	25 000	—	Robbins 161	6-yd³ cars + loco	203	5·[illegible]	—	418	—	—	—	554	—	Shale 12 000–18 000 lb/in²
Oahe, U.S.A.	26 ft 1 in	—	—	Robbins 930	Belt conveyor	540	8·0	50	—	—	12·0	140	—	—	Shale faulted bad ground
Paris, France	33 ft [illegible] in	7 400		Robbins [illegible]	Belt conveyor	8[illegible]	3·3	20		—	—	—	—	—	Limestone shale sandstone
Mangla, Pakistan	36 ft 8 in	8 500	—	Robbins 371	Ropebelt conveyor	1050	5·0	60	—	—	9·0	105	—	—	Sandstone shale

representative tunneling projects carried out using drill and blast, and excavating by tunnel boring machines (see also Table 8).

Softer rocks, such as tuff and sandstone, were examined in this project. For similar rock, the Hughes tool Betti 1 machine averaged 10 ft/hr while operating or 53 ft/day overall in a 10-ft diameter tunnel, 10,000 ft long in Navajo sandstone (Table 5). Other rates of advance varied with the geology along the tunnel.

A breakdown of operating time (Table 6) and repositioning time compared with drill and blast demonstrates the advantage of continuous boring over cyclic drill and blast (Table 7).

The advantages of machine boring compared to conventional drill and blast are:

1. Greater safety
2. Less overbreak and consequently less support
3. Decrease in size of labor crew
4. More uniform size of muck for disposal
5. Better direction control
6. Higher rates of advance

Disadvantages are:

1. High capital outlay
2. Limit of rock hardness which can be excavated
3. Time for manufacture of machine for a given job
4. Assembly time
5. Dismounting time
6. Reliability
7. Tunnel profile limited to circular
8. Ventilation and dust problem

TABLE 6

BREAKDOWN OF CYCLE, %, FOR ROCK TUNNELING MACHINES
(Ref. 2)

	Robbins (1955)	Robbins (1956)	Robbins (1962)	Robbins (1965)	Jarva (1965)	Jarva (1965)
Operating time	51	50	63	56	42	54
Maintenance repair	11	n.a.	19	19	n.a.	n.a.
Changing cutters	5	n.a.	11		n.a.	n.a.
Delays						
Support, ventilation, blockages	33	n.a.	7	n.a.	n.a.	n.a.
	100%		100%			

TABLE 7

CYCLE TIMES FOR TUNNELING
(Ref. 2)

Machine		Conventional	
Bore 2 ft	25 min	Drilling 6 ft	60 min
Reposition	2 min	Charge & fire	25 min
Bore 2 ft	26 min	Ventilating	15 min
Check line & maintenance	15 min	Mucking out	60 min
Reposition	2 min		
	69 min		160 min
	4-ft advance		5-1/2-ft advance
Average	9 5 ft/h	Average	2.05 ft/h

TABLE 8

KNOWN HARD ROCK TUNNELING MACHINES (Ref. 2)

Date	Manufacturer	Model	Diameter	Length, ft	Location	Application	Rock type	Hardness, lb/in²	hp	Thrust lb	Torque, lb ft	Cutters*	Wt. tons	Cost, £	Penetration, ft/h	Remarks
1954	Robbins	910	26 ft 3 in	—	Dakota, U S A	Hydroelectric	Shale	Soft	450	180 000	281 000	P D	125	110 000	8–12	Bad ground, faulted shale; conveyor problems
1955	Robbins	930	26 ft 3 in	23 000	Dakota U S A	Hydroelectric	Shale	Soft	450	192 500	360 000	P.D	130	125 000	8–12	
1956	Robbins	131	10 ft 9 in	14 800	Toronto, Canada	Sewer	Limestone, sandstone, shale	7 000–11 000	300	314 000	176 000	D	65	—	11	—
1957	Robbins	101	8 ft 0 in	n a	Pittsburgh, U S A	Sewer	Shale	Tough	400	117 600	138 000	P D	17	—	6–8	Excessive breakage of picks
1957	Robbins	102	8 ft 6 in	n a	Pittsburgh, U S A	Sewer	Shale, limestone	—	400	117 600	107 000	P.D	17	—	8–10	Excessive breakage of picks
1957	Robbins	103	9 ft 0 in	n a.	(a) Chicago, U S A (b) Canada	Sewer Mine	Limestone Iron ore	— —	400	117 600	138 000	P.D	17	—	(a) 2–4 (b) 10–12	Not successful in limestone Pick failures
1958	N C B	—	18 ft 0 in	—	(a) Breedon, U K (b) Dragonby U K	Exp Mine	Limestone Iron ore	18 000–20 000 4 000–8 000	750	990 000	—	G.D	300	250 000	(a) ? (b) 15	Operating
1958	Hughes	Exp	3 ft 4 in	n a	U S A	Exp	Various	3 000–30 000	75	226 000	n a	G	8	—	17–20	Later used by Gilsonite Co for production
1959	Robbins	351	29 ft 6 in	7 700	S Dakota U S A	Hydroelectric	Shale	—	680	250 000	684 000	P.D	175	180 000	8–12	—
1961	Robbins	161	16 ft 1 in	14 600	Tasmania	Hydroelectric	Shale	12 000–18 000	626	750 000	762 000	D	105	170 000	5–6	Dust a major problem
1961	Robbins	261	25 ft 8 in	20 000	Saskatchewan Canada	Hydroelectric	Shale	Soft	975	500 000	3 500 000	P	175	—	5–10	Badly faulted shale
1961	Hughes	—	8 ft 4 in	n a	n a	n a	Various	2 000–8 000	100	100 000	n a	G	16	—	2–12	Shield type
1962	Robbins	371	36 ft 8 in	8 500	Mangla, Pakistan	Hydroelectric	Sandstone, limestone	n a	1000	1 500 000	n a	P D	320	—	5–8	Cutters for hard and soft rock
1962	Robbins	71	7 ft 0 in 7 ft 6 in	n a	Potomac U S A	Sewer	Shale	n a	120	500 000	115 000	D	25	—	10	—
1963	Robbins	71A	7 ft 0 in	n a	Homer Wauseca, U S A	Mine	Iron ore	8 000–14 000	100	500 000	100 000	D	27	—	5	Cutter and access problems
1963	Hughes	—	6 ft 8 in	5 300	Mogollon Rim, U S A	Hydroelectric	Sandstone	11 000–15 000	250	600 000	n a	G	23	—	13	—
1964	Robbins	73	7 ft 0 in	111	Arizona, U S A	Water	Sandstone	2 000–12 000	n a	n a	n a	D	—	—	—	Project finished soon after machine started
1964	Lawrence	HRT-12	12ft 0 in	400	Richmond, U S A	Water	Shale metamorphic rocks	1 000–26 000	720	1 500 000	350 000	H	70	—	4	Failure due to slewing system, hydraulic pumps and anchor

TABLE 8 (CONT'D.)

Date	Manu-facturer	Model	Diameter	Length, ft	Location	Application	Rock type	Hardness, lb/in²	hp	Thrust, lb	Torque, lb ft	Cutters'	Wt, tons	Cost £	Penetration ft/h	Remarks
?	Jarva	?	6 ft 0 in	—	Philadelphia U S A	Sewer	Mica schist	—	225	43 000	—	B	25	—	4	—
1965	Robbins	R72	7 ft 0 in	n a	Shikoku Is Japan	—	Chlorite, schist	n a	—	—	—	D	—	—	—	—
1965	Robbins	R71	7 ft 0 in	n a	Bessams France	Water	Gneiss	20 000	150	200 000	—	D	36	71 000	5	—
1965	Jarva	Mk 8	7 ft 10 in	10 000	St Louis U S A	Sewer	Limestone chert	12 000–15 000	325	560 000	133 000	B	28	118 000	4–7	—
1965	Robbins	81 113	8 ft 6 in	26 000	Br Columbia Canada	Hydroelectric	Schist	5 000–20 000	—	—	—	D	28	72 000	—	Operating
1965	Robbins	81 118	8 ft 6 in	7 000	Freiberg Switzerland	Sewer	Sandstone	Soft	200	315 000	—	D	37	80 000	10	—
1965	Robbins	11 117	11 ft 6 in 12 ft 2 in	8 200	Baden Switzerland	Water	Sandstone	Soft	400	430 000	—	D	72	125 000	8–20	—
1965	Robbins	121	12 ft 8 in 13 ft 3 in	265 000	Azotea U S A	Water	Shale, sandstone	3 000–9 000	400	480 000	—	D	90	144 000	11 5	Operating
1965	Jarva	Mk [illegible]4	13 ft 8 in	1 600	Philadelphia U S A	Sewer	Limestone, hornblende	6 000–25 000	540	866 000	275 000	B	80	193 000	1–8	—
1965	Calweld	—	15 ft 11 in	6 900	Minnesota, U S A	Sewer	Sandstone	n a	n a	n a	n a	D	n a	n a	3	—
1965	Hughes	Ben[illegible]	19 ft 10 in 21 ft 2 in	10 000	Navajo U S A	Irrigation	Shale, sandstone	5 000–6 000	1100	1 400 000	n a	G D	260	n a	10–17	—
1965	Robbins	341	33 ft 8 in	7 400	Paris France	Metro	Limestone sand/clay	—	1000	1 500 000	n a	D	500	535 000	3 3	Face under compressed air sealing difficulties
1966	Demag	—	6 ft 6 in	2 600	Dortmund Germany	Sewer	Sandstone	4 000–10 000	200	224 000	n a	D	40	n a	6–9	—
1966	Robbins	104 120	9 ft 11 in 10 ft 7 in	41 800	Blanco U S A	Water	Shale	—	300	388 000	n a	D	55	n a	14 3	—
1966	Robbins	104 121A	9 ft 11 in 10 ft 7 in	26 400	Oso U S A	Water	Shale	—	300	388 000	n a	D	55	n a	14	Achieved world record
1966	Jarva	Mk 14	10 ft 8 in	4 200	St Louis U S A	Sewer	Limestone	12 000 19 000	540	866 000	275 000	B	80	193 000	4	—
1966	Calweld	—	11 ft 4 in	10 000	Coventry U K	Sewer	Sandstone marl	4 000–12 000	200	560 000	320 000	D	—	—	4	Operating
1966	Habegger	836	11 ft 6 in	66 000	Japan	Railway [illegible]	Tuff andesite	5 000–34 000	650	515 000	500 000	P	85	134 000	8	Operating
1966	Calweld	—	12 ft 7 in	24 000	Japan	—	Sandstone clay	—	—	—	—	D	—	—	4 5	Operating
1967	Demag	TVM [illegible] 23	7 ft 0 in	4 600	Stuttgart Germany	Water	Limestone	29 000	300	—	—	D	45	—	5	Operating
1967	Wirth	TBM2[illegible]	7 ft 0 in	800	Austria	Water	Granite	1 045 000	250	400 000	100 000	G	32	—	5	Being modified

TABLE 8 (CONT'D.)

Date	Manufacturer	Model	Diameter	Length, ft	Location	Application	Rock type	Hardness lb/in²	hp	Thrust, lb	Torque, lb ft	Cutters*	Wt. tons	Cost, £	Penetration, ft/h	Remarks
1967	Krupp	—	9 ft 10 in	—	Germany	Mine	Shale	—	—	—	—	P	37	—	12	Crawler-mounted
1967	Jarva	Mk 8	10 ft 0 in	3 500	St Louis, U S A	Sewer	n a	n a	325	560 000	133 000	B	30	118 000	n a	—
1967	Jarva	Mk 11	10 ft 0 in	—	Minesville, U S A	Iron ore mine	Hematite, gneiss	n a.	440	866 000	275 000	B	45	157 000	n a	Operating
1967	Robbins	111/117	11 ft 0 in	—	Zurich, Switzerland	Water	n a	n a	400	430 000	—	D	72	—	n a	Operating same machine as Baden project
1967	Robbins	?	11 ft 0 in 14 ft 5 in	55 000	Melbourne, Australia	Sewer	Mudstone	—	n a	n a.	n a	n a	n a	n a.	n a	Operating
1967	Habegger	836	11 ft 6 in	19 000	Chur, Switzerland	Hydroelectric	Shale, quartz, limestone	14 000–21 000	650	515 000	500 000	P	85	134 000	3–6	Operating
1967	Jarva	Mk 14	13 ft 0 in	—	Cleveland, U S A	Iron ore mine	Hematite, argillite	n a	540	866 000	275 000	B	80	193 000	n a	Operating
1967	Calweld	—	25 ft 7 in	18 000	Newhall, U S A	Irrigation	Sandstone, gravel	3 000–15 000	n a	n a	n a	C	250	n a	4 (est.)	Operating
1967	Habegger	829	9 ft 6 in	—	Stuttgart, Germany	Water	—	—	550	—	—	P	65	—	—	Operating
1967	Robbins	?	18 ft 0 in	—	White Pine Copper Co, U S A	Copper mine	Cu ore	15 000–30 000	1500	1 500 000	n a	D	n a	n a	n a	Due to start late 1967
1968	Robbins	?	34 ft 0 in	7 000	Liverpool, U K	Road	Sandstone marl	5 000–10 000	1100	n a	n a	D	n a	n a	n a.	Due to start 1968
1968	N C B	Exp	6 ft 0 in	—	n a	Exp	Limestone	22 000	95	n a	n a	D	n a	n a	n a.	Due to start 1968
1968	Jarva	Mk 14	Under construction		—	—	—	—	—	—	—	—	—	—	—	—
1968	Habegger	836	11 ft 6 in	—	Japan	Rail pilot	—	—	650	515 000	500 000	P	85	n a	—	Due to start 1968
1968	Habegger	840	13 ft 3 in	—	Japan	Rail pilot	—	—	—	—	—	—	—	—	—	Due to start 1968
1968	Wirth	TBM300	9 ft 6 in 11 ft 0 in	—	Under consideration	—	—	—	—	—	—	—	—	—	—	—

*P, picks, D, disc rollers, G, gear rollers, B, button rollers

9. High power requirements

10. Experience and advance conditions

Operating problems:

1. Boring and cutters must be improved

2. Hard rocks require high thrusts

3. Collecting system for sticky materials

A performance prediction curve was plotted from existing data, which shows that the cubic feet per horsepower decreases very rapidly with increase in compressive strength (Figure 9). While these data show a good correlation between compressive strength and overall performance and compressive strength of rock is used widely by the tunnel boring industry as a measure of boreability, in general, the compressive strength of rock is not a reliable measure of the rate of penetration of cutters into the rock or of the overall advance rates. The relationship of these factors to the physical properties of rocks is discussed later in this report.

In discussing the function and efficiency of tunneling machines, Hamilton (Ref. 3) indicated that while emphasis in the past had been upon rock cutting or boring ability, emphasis should be upon the performance of the whole system.

Factors not directly related to fracturing of the rock are: (1) noise and safety, (2) ground support, (3) probe drilling, (4) muck handling and transport, and (5) other backup systems. Items of importance in the boring systems are: (1) penetration rate, (2) advance rate, (3) tunneler availability, (4) system utilization, (5) downtime, (6) boring time, and (7) standby time.

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3. Hamilton, W.H., 1972, "Role of the Tunneling Machine," Proc. RETC, p. 1093.

Factors which affect the advance rate may be classed as (1) *penetration rate*, and (2) *system utilization*. Specific energy, penetration rate, and tunneler availability have all improved in recent years because of equipment improvement (Figures 10 - 12). Backup capability has improved more slowly (Figures 13 & 14). A projected increase in performance indicates a possible 80% utilization by 1980 (Figure 15). For the Port Huron project, an 18-ft 4-in. diameter tunnel in shale, 31,555 ft long, the advance rate and related factors improved over the period of the project because of start-up, shakedown, crew training, replacement of parts, and bad ground encountered in April and May (Figures 16 - 18).

It was concluded in Reference 3 that increase in penetration alone does not result in an increase in advance rate, and that many projects could increase their advance rate without increasing the penetration rate by improving the system utilization.

Gaye (Ref. 4) showed schematically the relationship between penetration rate, specific energy, power and thrust (Figure 19). In general, there is an optimum combination of power and thrust to give an optimum value of penetration rate per kilowatt hour for a given rock.

A rock number N_R is defined by:

$$N_p = \frac{f_c}{E_s} \tag{4}$$

where

f_c = compressive strength

E_s = specific energy

4. Gaye, F., 1972, "Efficient Excavation - Cutting Head Design of Hard Rock Tunneling Machines," *Tunnels and Tunneling*.

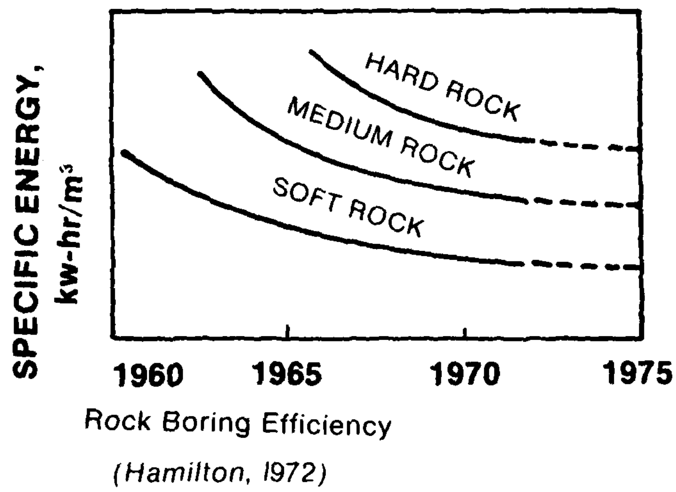


FIGURE 10 - Relative Rock Boring Efficiency (Ref. 3)

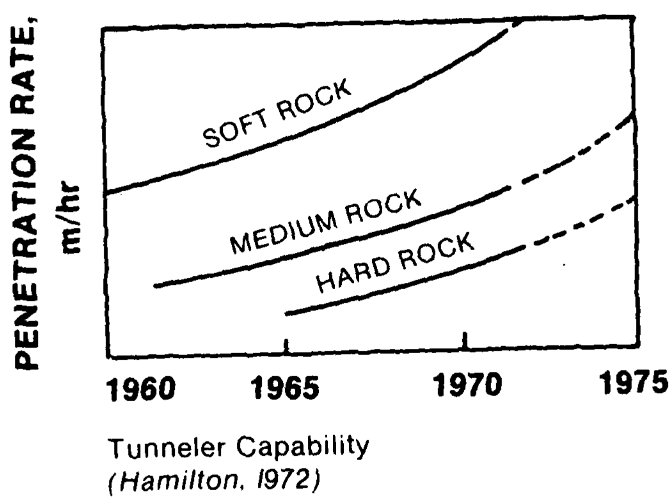
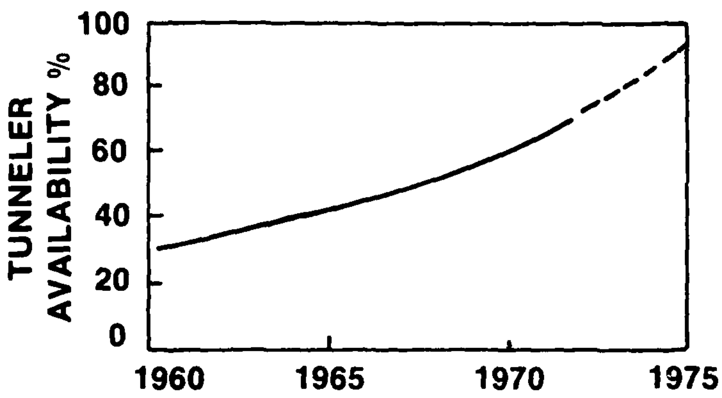
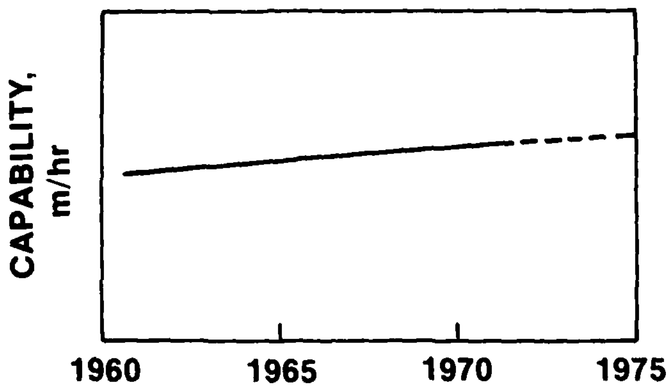


FIGURE 11 Tunneler Capability (Ref. 3)



Tunneler Availability
(Hamilton, 1972)

FIGURE 12 - Tunneler Availability (Ref. 3)



Back-up Systems Capability
(Hamilton, 1972)

FIGURE 13 - Backup Systems Capability (Ref. 3)

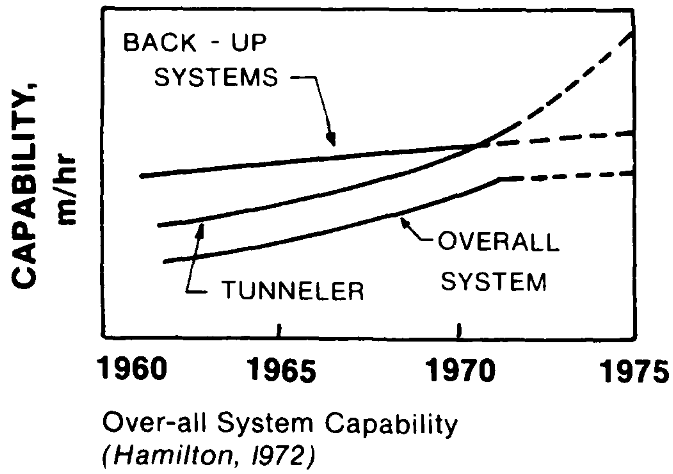


FIGURE 14 - Overall System Capability (Ref. 3)

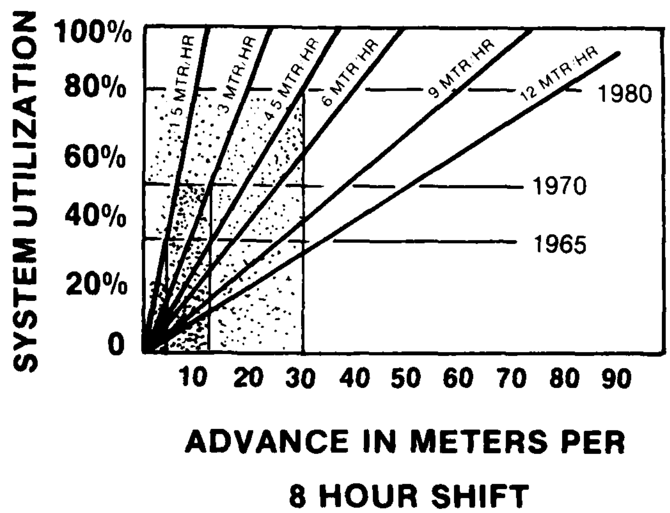


FIGURE 15 - Effect of Penetration Rate and System Utilization on Advance Rate (Ref. 3)

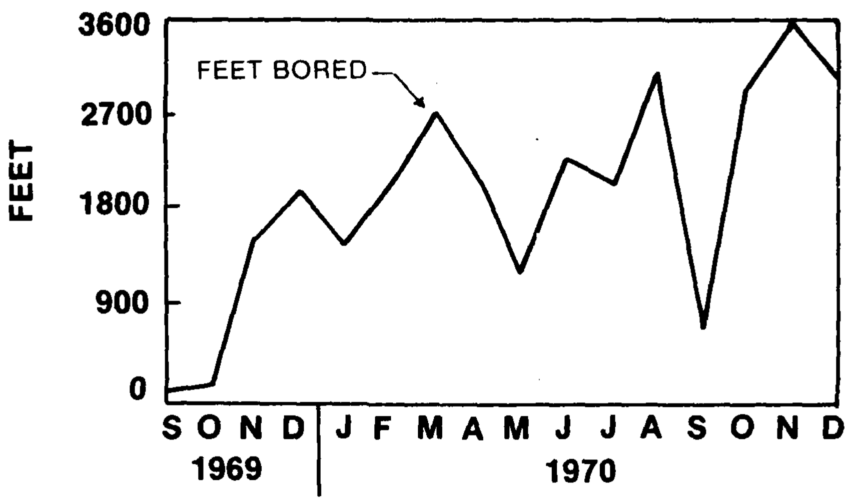


FIGURE 16 - Feet Bored Per Month (Ref. 3)

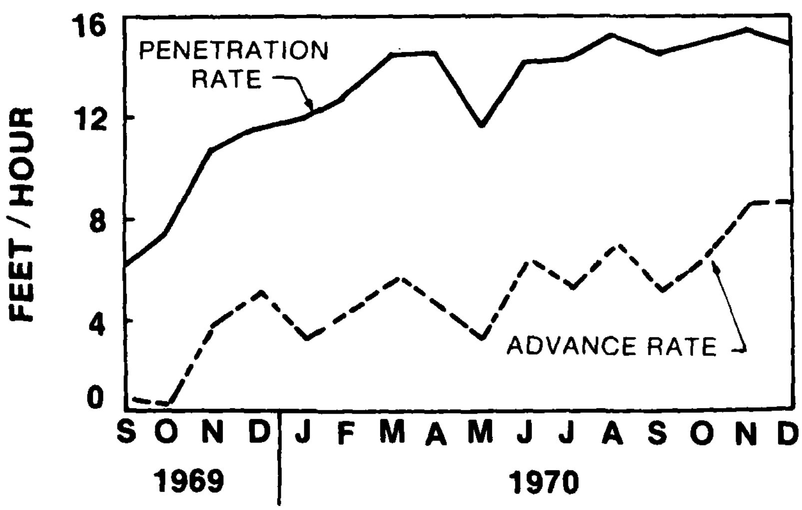


FIGURE 17 - Penetration and Advance Rates, Port Huron Project (Ref. 3)

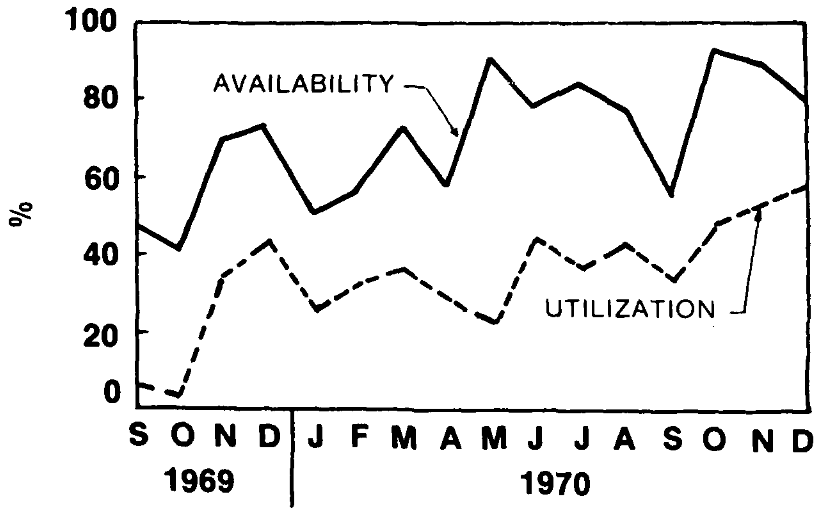


FIGURE 18 - Availability and Utilization, Port Huron Project (Ref. 3)

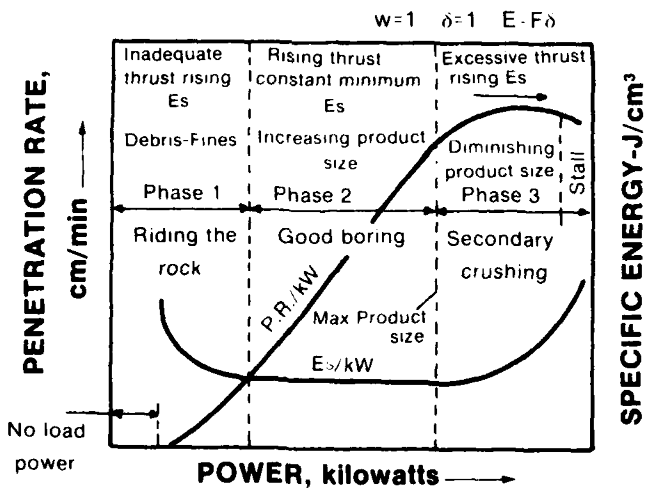


FIGURE 19 - Characteristic Performance Curve: Rock Boring (Ref. 4)

This, however, may be used only as an approximate guide to machine performance and must be used in a statistical manner.

For an 18-ft diameter tunneling machine with an outer and inner counter rotating head, Gaye (Ref. 4) also found that the penetration increased almost linearly in limestone with thrust and power for both the inner and outer heads (Figures 20 - 22). The behavior was quite different for iron ore (Figures 23 - 25) where critical upper and lower penetration rates and critical upper and lower thrusts were well defined.

The progress in the Nast tunnel as of 1972 was reported by Geary (Ref. 5). At that time, 7,200 ft had been excavated with few good performances. Disc cutters gave up to 6 ft/hr, but snap rings holding the discs to the hubs failed. Muck from the disc cutters was larger and easier to handle than that from button cutters which gave an average cutting rate of 3 ft/hr.

The tunnel was driven in hard gneissoid granites and gneisses containing felsitic dikes and pegmatite veins. The rock was moderately jointed by two sets of vertical joints. Shear zones were encountered of 5 to 150 ft in width, but little water was encountered. The compressive strength of the rock varied from 18,020 to 24,430 psi.

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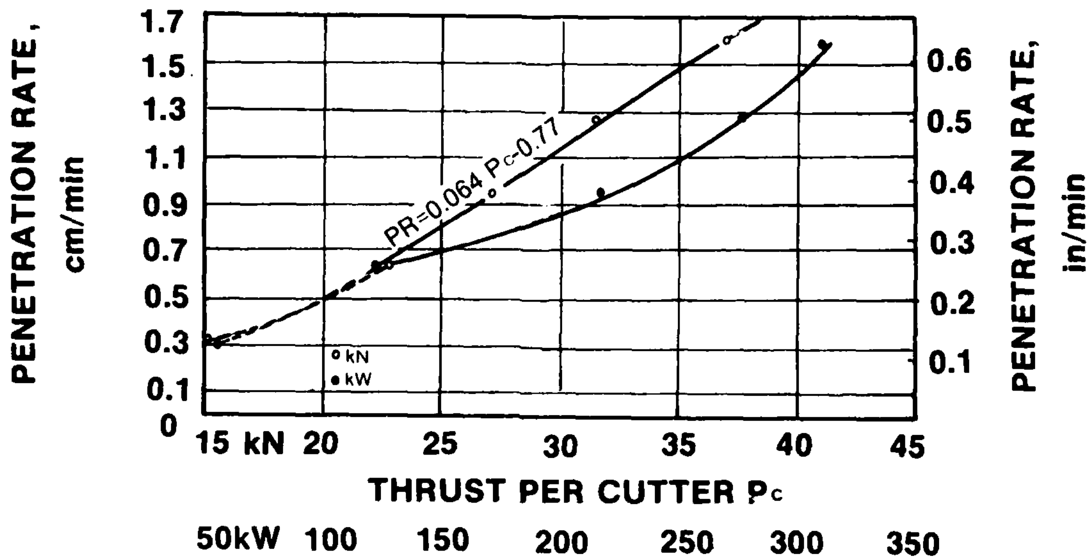
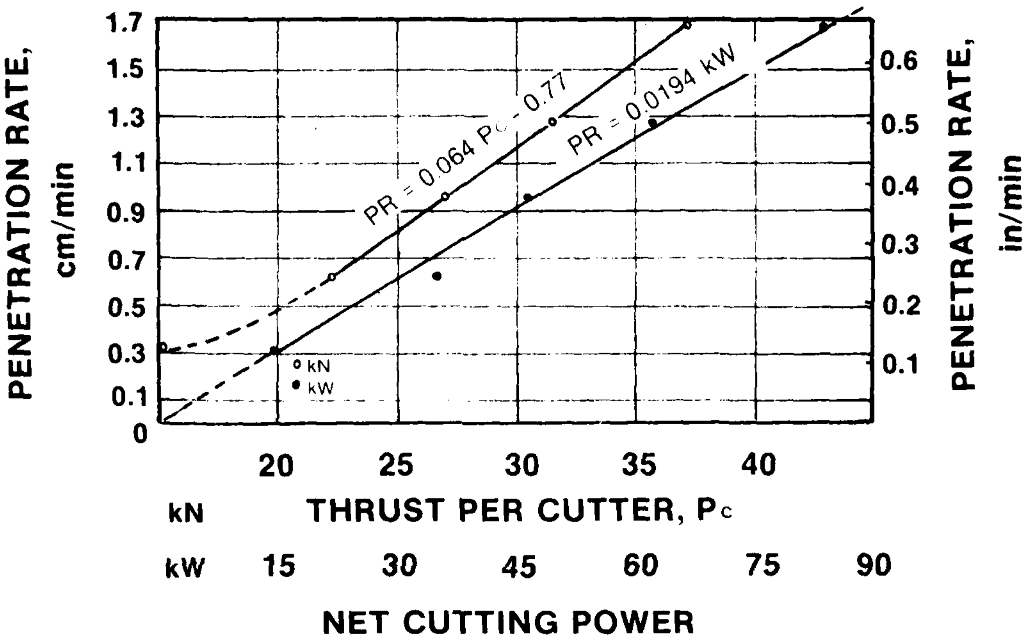
5. Geary, D.W., 1972, "Nast Tunnel Excavation History," Proc. RETC, AIME.



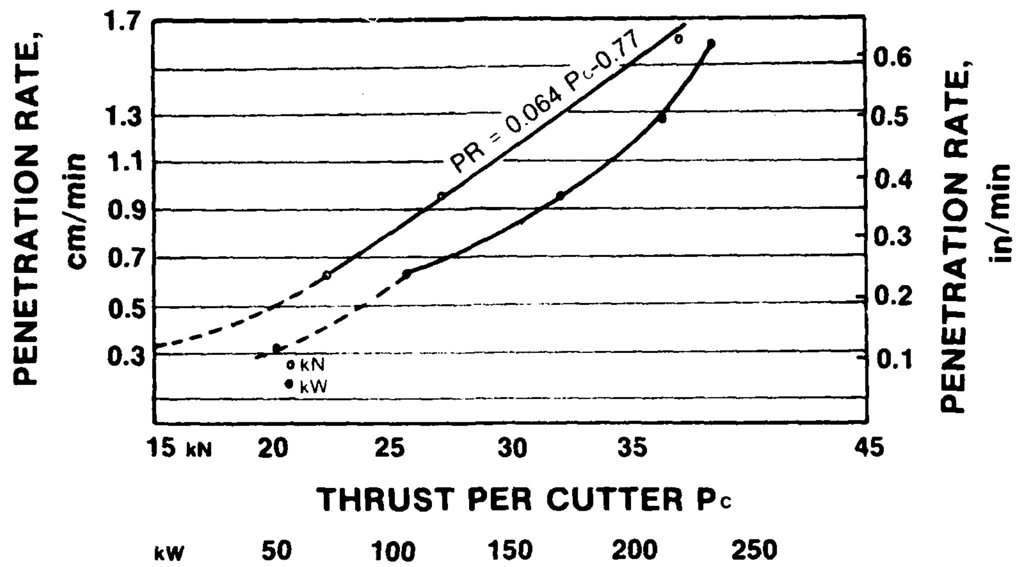
5.5m (18 ft) dia NCB tunneling machine (88 Hughes SCM roller cutters). Instantaneous cutting and loading performance-worn cutters-at end of trial. Breedon Limestone.
f_c (11 = 107 MN/m^2 (15,500 lbf/in^2)
Shore Sclerescope - S(10) = 57.5
Specific energy (av.) - E_s = 53 J/cm^2 (7700 in-lbf/in^3)
NCB Cone indenter - D/1(20) = 4.72
N_R (worn cutters) = f_c/E_s = 2.01
(Ref. 4)

FIGURE 20 - Total Machine Power (Less no Load Power)



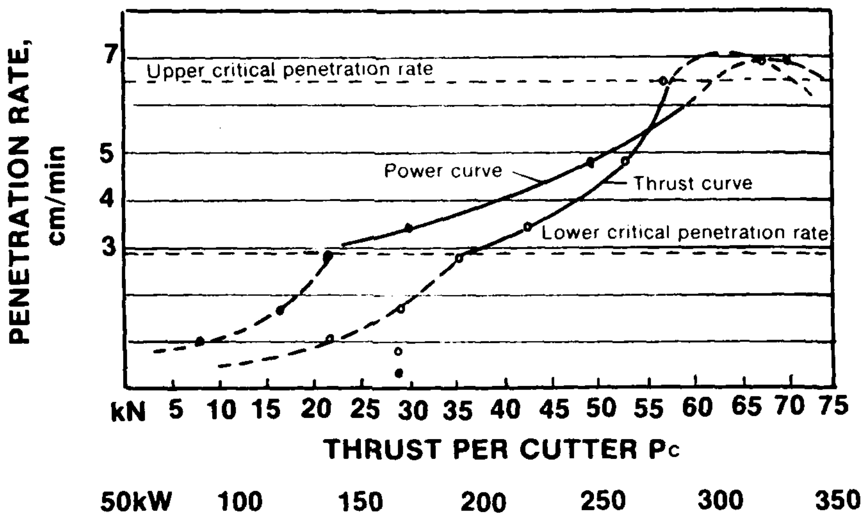
Inner head (8.7 rpm) - 22 Hughes SCM roller cutters
Instantaneous cutting performance (no loading)
Breedon Limestone
Specific energy (av.) - E_s = 52 J/cm^3 (7550 in-lbf/in^3)
[illegible] (worn cutters) - f_c/E_s = 107/52 = 2.06
(Ref. [illegible])

FIGURE [illegible] - Net Cutting Power



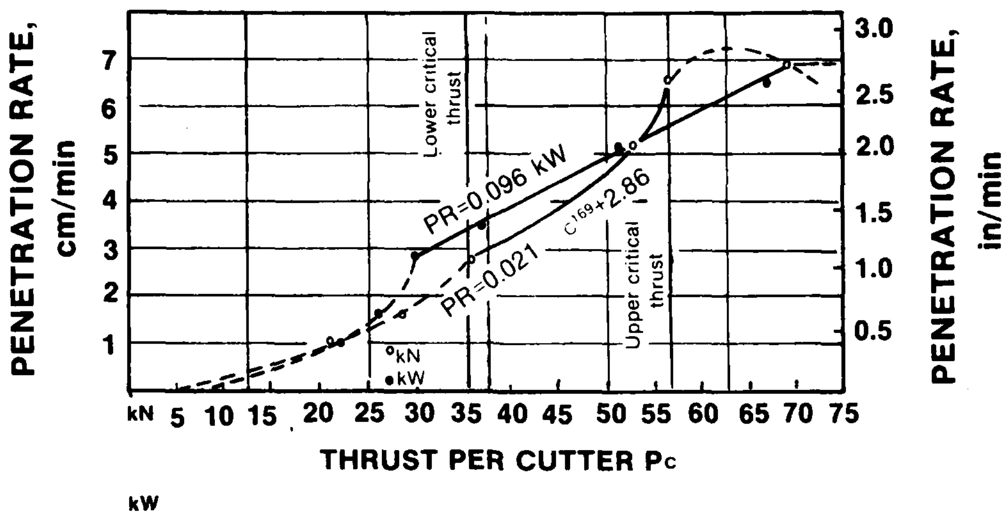
Outer head (2.86 rpm) - 66 Hughes SCM roller cutters.
Instantaneous cutting and loading performance.
Breedon Limestone.
Specific energy (av.) - E_s = 54.4 J/cm^3 (7900 in-lbf/in^3)
N_R (worn cutters) - f_c/E_s = 107/54.4 - 1.97
(Ref. 4)

FIGURE 22 - Net Cutting and Loading Power



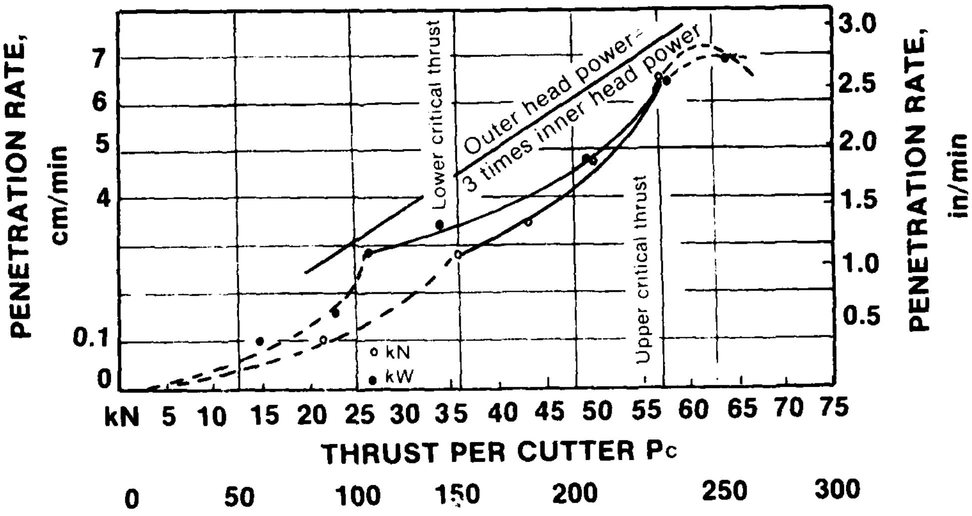
5.5m (18 ft) diam. NCB tunneling machine. Hughes DGX discs and SCM roller cutters. Instantaneous and loading performance.
Dragonby iron ore (33.22 MN/m^2 - 4820 lbf/in^2)
NCB Cone indenter hardness - 1.041
Av. specific energy - 12.15 J/cm^3 (1760 $in\text{-}lbf/in^3$)
N_R = 33.22/12.5 = 2/74
(Ref. 4)

FIGURE 23 -Total Machine Power Cutting and Loading (Less no Load Power)



Inner head (8.7 rpm). Hughes DGX discs and SCM roller cutters. Instantaneous cutting performance.
Dragonby iron ore.
NCB Cone indenter hardness - 1.041
Equiv. comp. stress - 33.22 MN/m^2 (4820 lbf/in^2)
Av. specific energy - 10.50 J/cm^3 (1525 $in\text{-}lbf/in^3$)
$N_R = f_c/E_s$ = 33.22/10.50 = 3.17
(Ref. 4)

FIGURE 24 - Net Cutting Power



Outerhead (2.36 rpm). Hughes DGX discs.
Instantaneous cutting and loading performance.
Dragonby iron ore.
NCB Cone indenter hardness - 1.041
Equiv. comp. stress - 33.22 MN/m^2 (4820 lbf/in^2)
Av. specific energy - 12.9 J/cm^3 (1870 in-lbf/in^3)
$N_R = f_c/E_s = 33.22/12.90 = 2.57$

FIGURE 25 - Net Cutting and Loading Power

Three major delays consuming 25% of the elapsed time occurred because of required modifications of the cutterhead, and replacement of the cutterhead bearings. Other modifications were also made. Frequently, large blocks loosened by the cutters or the pressure pads fell into the tunnel in front of the cutterhead or to the rear of the cutter.

Utilities included ventilation, track, power, compressed air, cutterhead cooling water, pumps for discharge water, alignment and grade lasers. The best six weeks production was obtained in a section of the tunnel where there was no fallout from the roof and ribs. Machine (Wirth) statistics include diameter 9 ft 9 in., first cutterhead with 26 cutters, a second cutterhead was flat with 29 cutters, and thrust was 450,000 to 720,000 lbs (Figure 26). Typical machine avaliability is shown for a six week period in Figure 26.

Two of the sewer system tunnels in Chicago had been completed in 1972 (Ref. 6). Subsurface exploration indicated structurally excellent rock (limestone) at the 200-ft level, the two completed systems being in Niagara limestone 200 to 250 ft below the surface.

For the LeGrange-Brook section, tunnel bids were let in June 1968, specifications stipulating that machines be designed to minimize disruption in urban areas, to develop the know-how of contractors to excavate future tunnels more economically, and for the potential of eliminating concrete lining.

The contract allowed 930 days for construction, a delivery time of 8 months for the machine, and called for 17,500 ft of 12-ft clear diameter tunnel, the bore to be 13 ft 10 in. A 250-ft tail tunnel and 400 ft of

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6. Irons, J. and D. Westfall, 1972, "Rock Tunnels Recently Completed in Chicago," Proc. RETC, AIME, p. 1063, Chicago, Illinois.

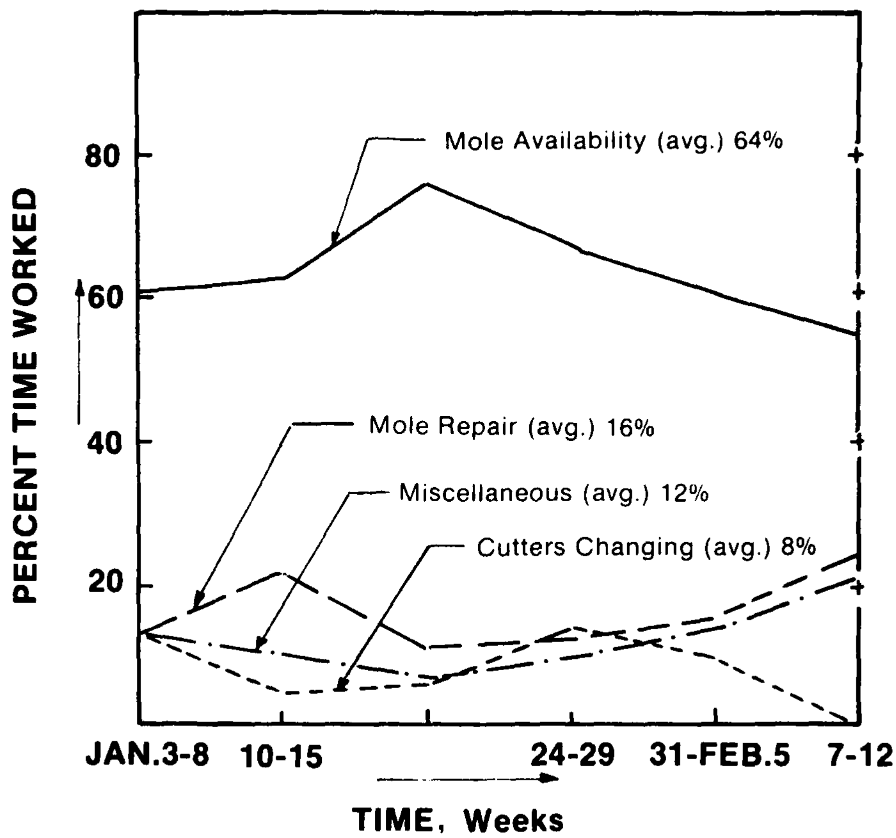


FIGURE 26 - Time Distribution - NAST Project (Ref. 4)

the tunnel were excavated by drill and blast to make room for the machine, which was delivered in 9 months. It was 37 ft long and powered by six 100 hp motors, with 27 disc cutters, two gripping pads, and jacks to move the machine 2.5 ft per push. Single disc cutters were chosen based upon the rock compressive strength of 15,000 to 25,000 psi.

Electrical power was supplied as 480 volts, with ventilation through a 30 in. vent line. Broken rock was carried by a 480 ft conveyor to muck cars of 4.4 cu yd capacity, and each 2.5 ft advance filled 10 muck cars. The gripping pads were moved while muck cars were being changed.

Machine guidance was by means of laser beams, two misalignments occurring because of failure to check the beam. There were two 90° curves excavated which added significantly to the costs because the conveyor systems were unbolted and progress was slowed to prevent unbalancing the machine. To avoid this difficulty in the future, 400 ft radius curves were to be required. Penetration rates and boring efficiencies were considered to be good (Figure 27). Water was encountered coming from horizontal bedding planes, and grouting was carried out in holes drilled from the surface. The smooth bore of the tunnel and the strength of the rock obviated the need for concrete lining. The excavation was completed in September 1970, and the machine was backed out the full length of the tunnel (17,500 ft).

A machine of the pilot pull type was used to excavate the rock in the Lawrence Avenue tunnel, 13 ft 8 in. diameter, 12,670 ft long. For an enlarged section, the crown of the tunnel was blasted after it had been excavated by the machine.

The Crawford Avenue tunnel was 16 ft 10 in. diameter and 18,300 ft long. The machine was equipped with 54 conical tungsten carbide insert-type cutters, with a 260 ft conveyor loading into cars with 10 cu yd

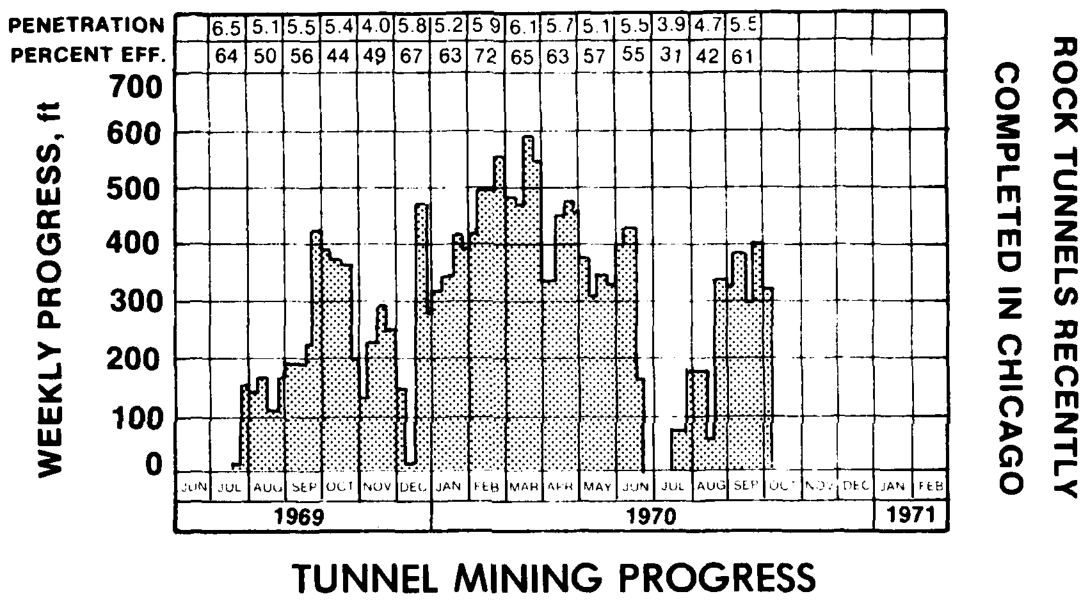
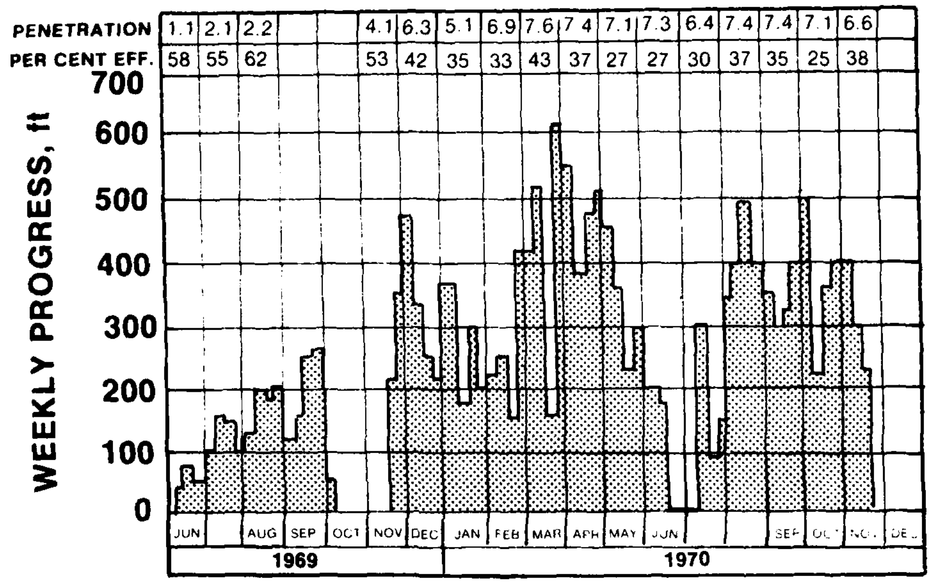


FIGURE 27 - Tunneling Progress Rates Achieved on the 13' - 10" Diameter LaGrange-Brookfield Project (13-A) (Ref. 6)

capacity. Penetration rates varied from 6.6 to 7.6 per hour with 25 to 43% efficiency (Figure 28).

It was felt that penetration rates and efficiencies could not be compared from project to project because of variable rock strengths, different types of cutters, and problems which were peculiar to a given project.



TUNNEL MINING PROGRESS

FIGURE 28 - Tunneling Progress Rates Achieved on the 16' - 10" Diameter Crawford Ave (18E-Ext. A) Project (Ref. 6)

WATER JET ASSISTED TUNNEL BORING

An extensive research project to determine the effects of high pressure water jets in assisting tunnel boring in granite was carried out by Wang, et al (Ref. 7), to determine possible increases in rates of advance, reduction in cutter wear, and ultimate reduction in costs.

The plan of the research project was to submit granite from a field testing site to slot cutting tests with high pressure water jets in the laboratory and to utilize this test data to design a water jet manifold for installation on a tunnel boring machine so that the nozzle location could be adjusted with respect to the cutters.

The laboratory slotting tests showed that the depth of cut decreased rapidly with increasing jet traverse velocity with the depth of cut ranging from 0.25 in. for a low traverse velocity to a leveling off just below 0.10 in. depth for higher velocities (Figure 29). It was also found that the depth of slot was 50% greater when the jet cut into the slot made by a disc cutter (Figure 30).

The field tests indicated that the water jets were effective when they were applied under the cutters (Figures 31 & 32). The average data for 0.012 in. diameter nozzles compared with unassisted mechanical cutting show improvements in rates of advance of 40% at 3,000 psi thrust, 46% at 3,500 psi thrust, and 48% at 4,000 psi thrust. Water jet pressures varied between 37 and 50 ksi. The total power of the water compression equipment was 450 hp.

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7. Wang, Fun-Den, R. Roberts, and J. Olsen, February 1976, "Water Jet Assisted Tunnel Boring," EMI, Colorado School of Mines, Golden, Colorado.

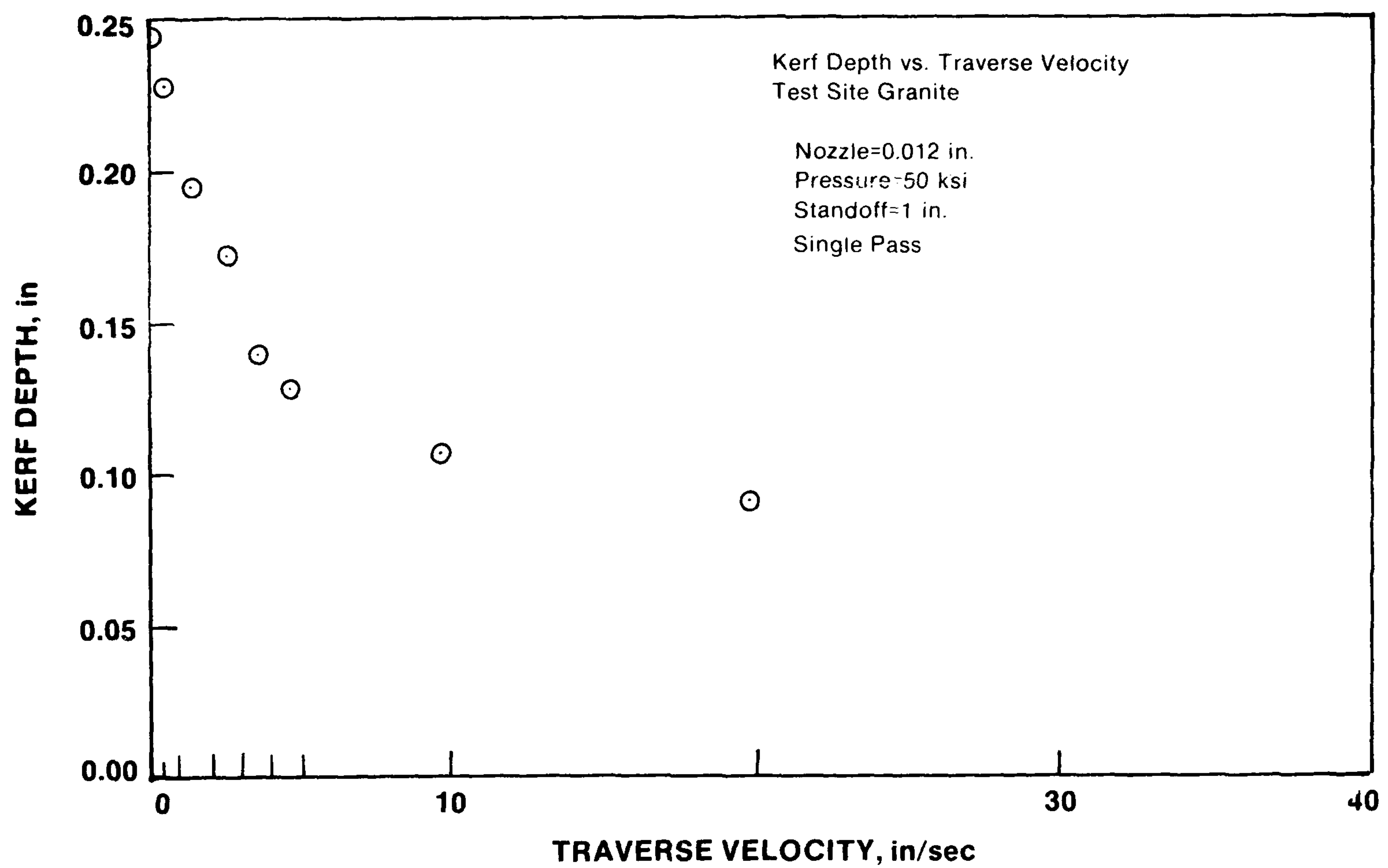

FIGURE 29 - The Effect of Traverse Velocity on Kerf Depth (Ref. 7)

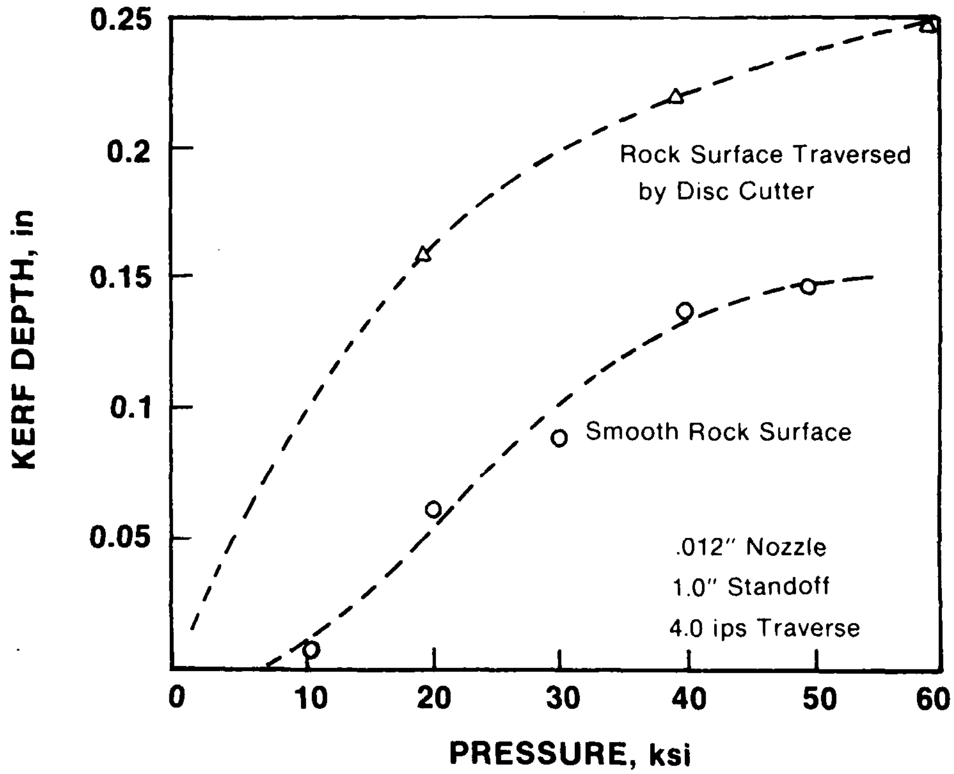

FIGURE 30 - Complementary Effect of Mechanical Disc Cutting on Water Jet Kerfing in Red Granite (Ref. 7)

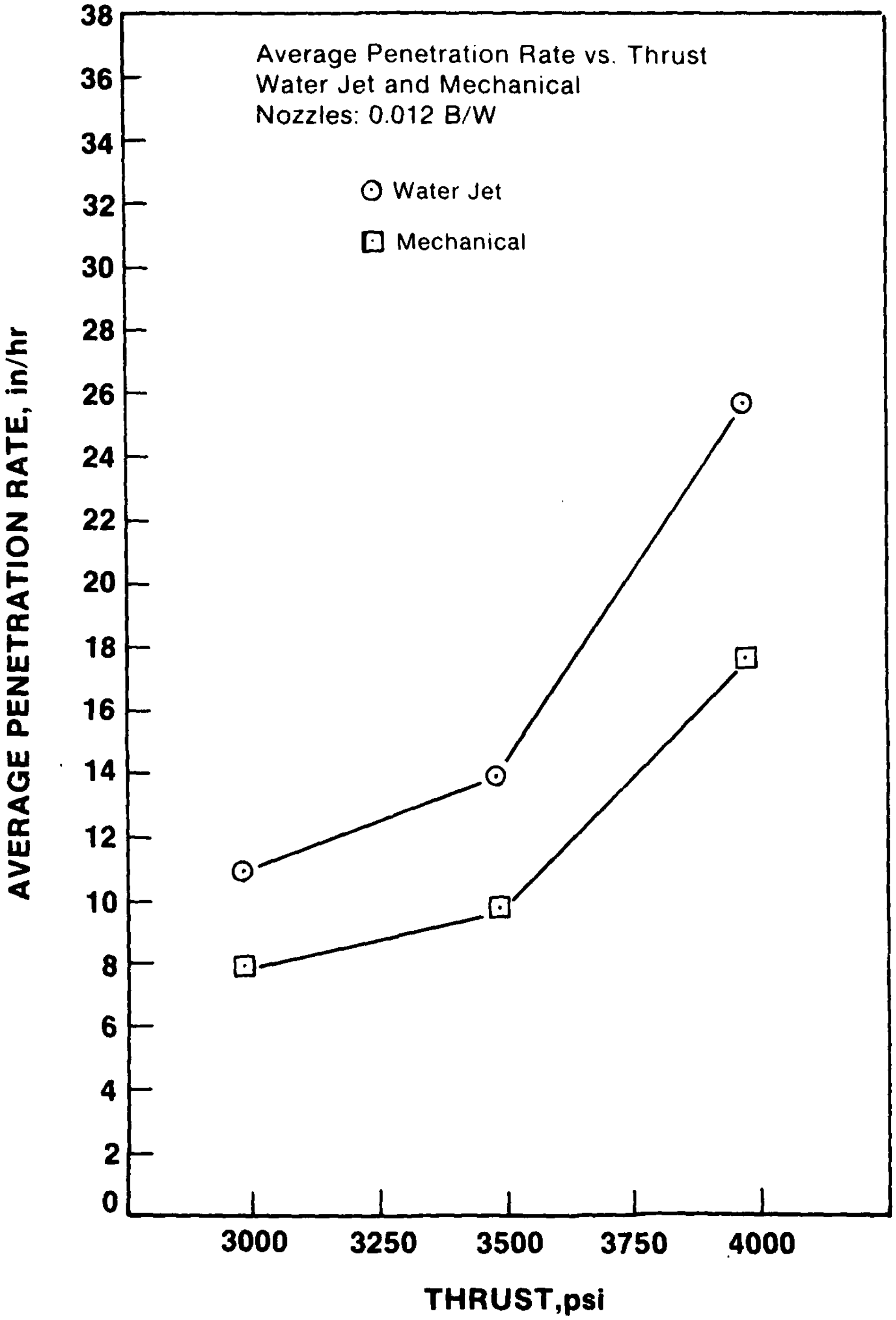

FIGURE 31 - Average Penetration Rate vs Thrust (Ref. 7)

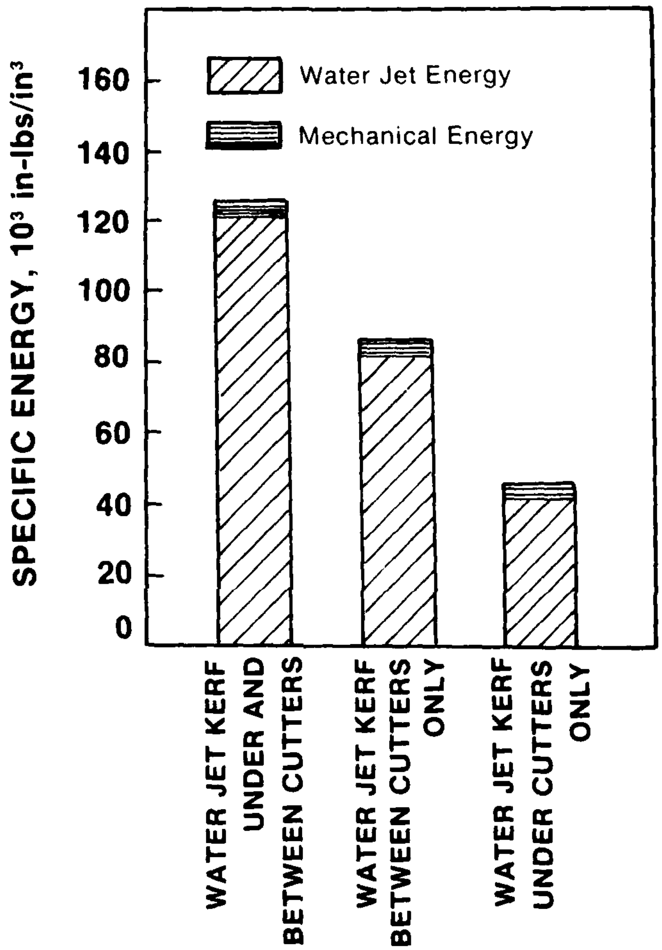

FIGURE 32 - Power Requirements Versus Different Water Patterns on Granite, 0.2" Water Jet Kerf (Ref. 7)

The water jet also reduces the thrust required for a given thrust and spacing (Figure 33), while the kerf cut by a water jet increases with cutter spacing (Figure 34).

The estimated cost savings when water jets were used to assist mechanical cutting varied with the number of nozzles (horsepower of equipment used) and the percent increase in rate of advance (Figure 35). Even moderate cost savings of 10 to 20 percent result in very significant overall savings on a given project. Also, inasmuch as the granite tested was very difficult to bore with a tunneling machine, equivalent or greater savings could be achieved in many harder and softer rocks.

While the high pressure water jet assist tests have been conducted largely on hard granite, there is considerable information in the literature on the jet cutting of softer rocks. Many sandstones are quite susceptible to cutting because of their porosity, while some shales are difficult to cut.

A comparison (Ref. 8) of the capability of jets for slotting softer rocks (Figure 36) shows that for slow traverse rates, the variation of penetration with pressure is much greater than for faster rates, although the relative values are somewhat comparable. It is noteworthy that at 1 m/sec and 15,000 psi pressure, a jet of 0.012-in. diameter will cut a slot almost twice as deep in sandstone as a 50,000 psi jet in granite. Thus, for soft rocks, the hp for water jets will be much smaller than for hard rocks.

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8. Harris, H.D. and M. Mellor, 1974, "Penetration of Rocks by Continuous Water Jets," Proc. Second International Symposium on Jet Cutting Technology, Cambridge, England.

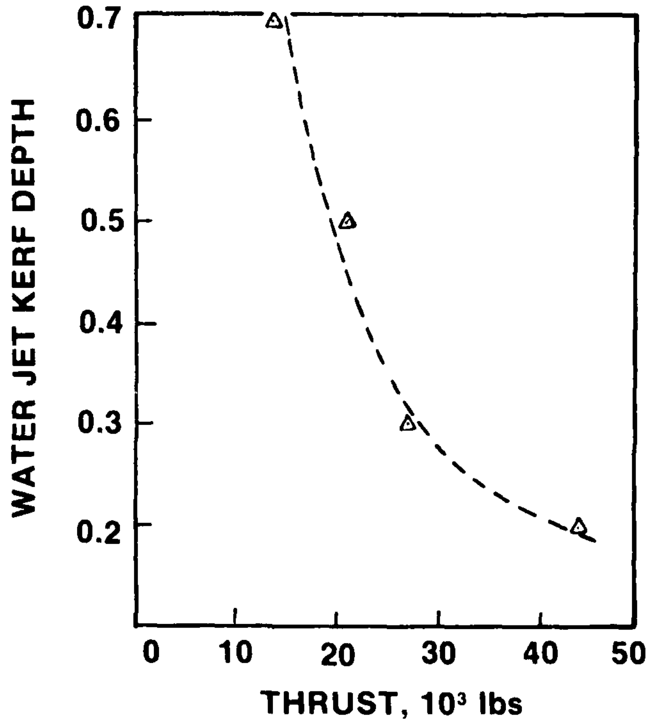

FIGURE 33 - Water Jet Kerf Depth vs Thrust at Constant Spacing (2.5 inches) (Ref. 7)

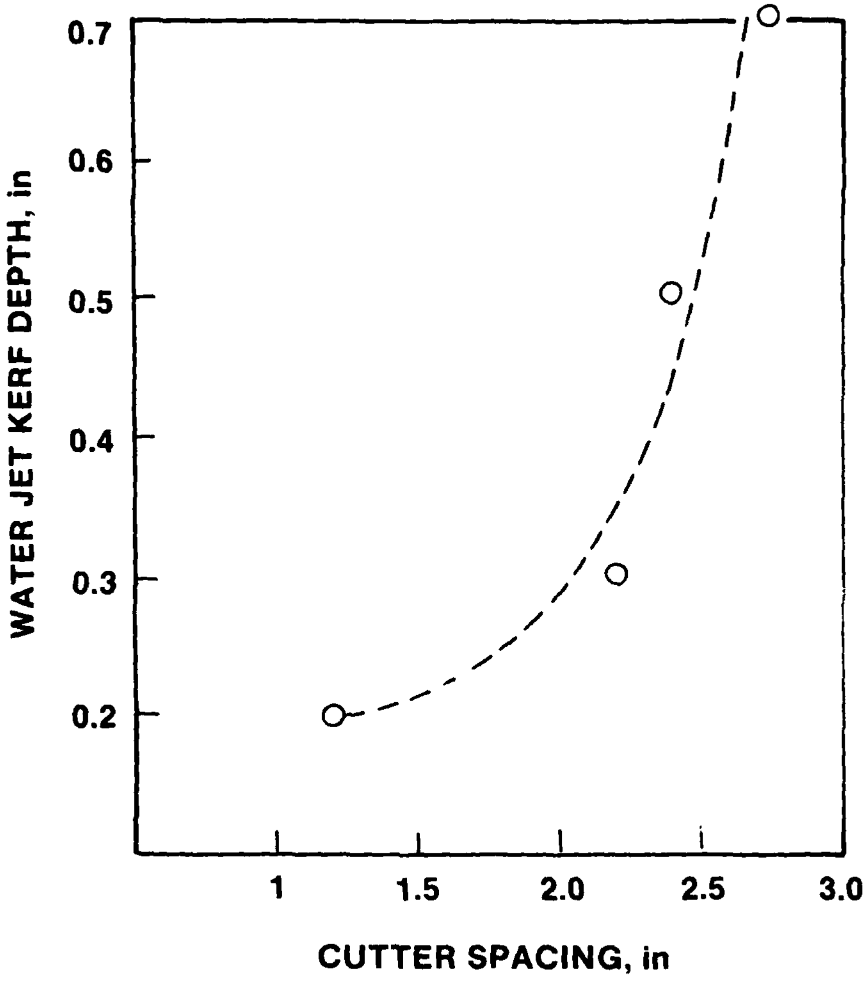

FIGURE 34 - Water Jet Kerf Depth vs Cutter Spacing at Constant Cutter Thrust (20,000 pounds) (Ref. 7)

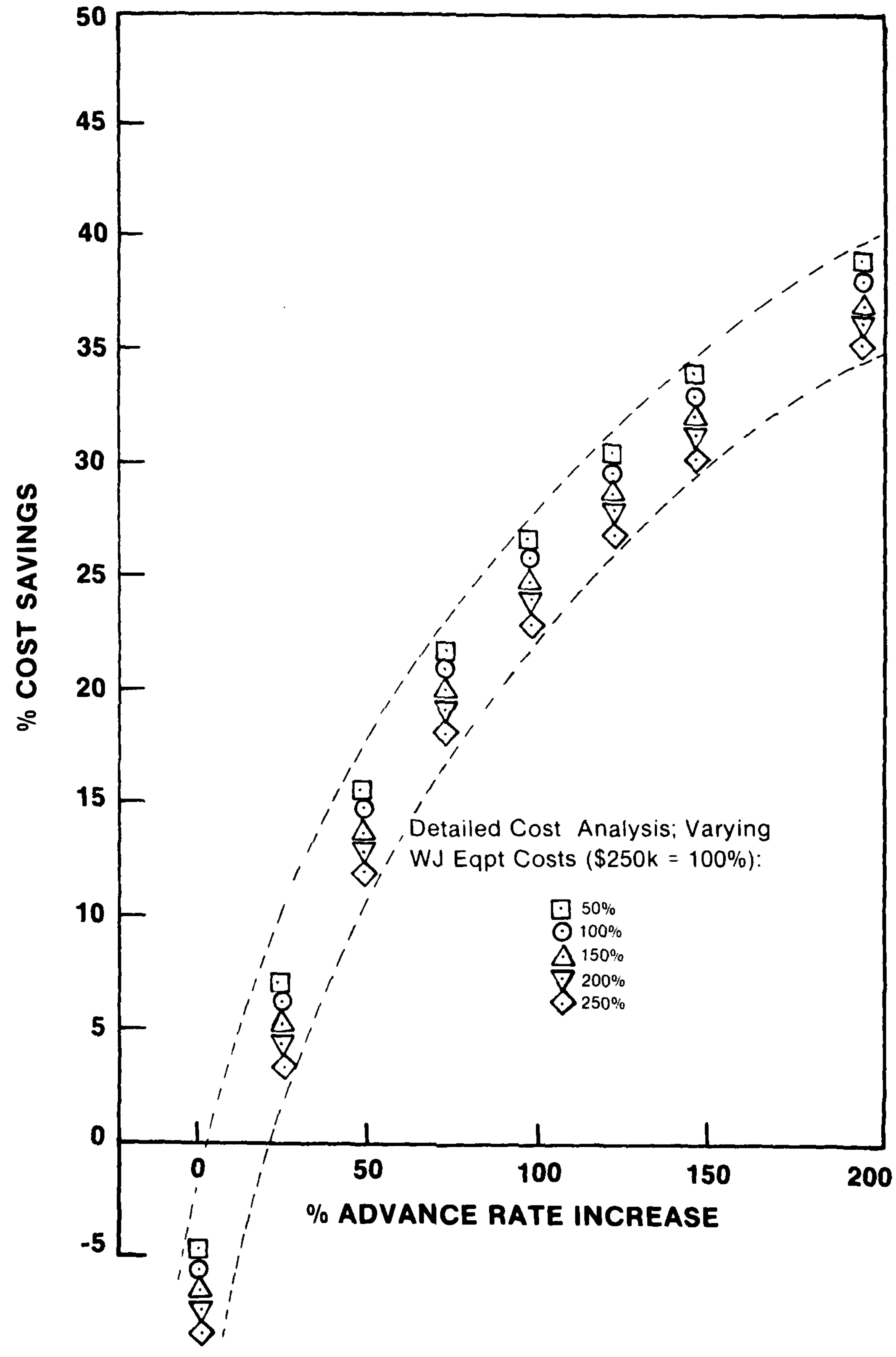

FIGURE 35 - Percent Cost Savings (Estimated) vs Advance Rate Increase, Water Jet Assisted Boring (Ref. 7)

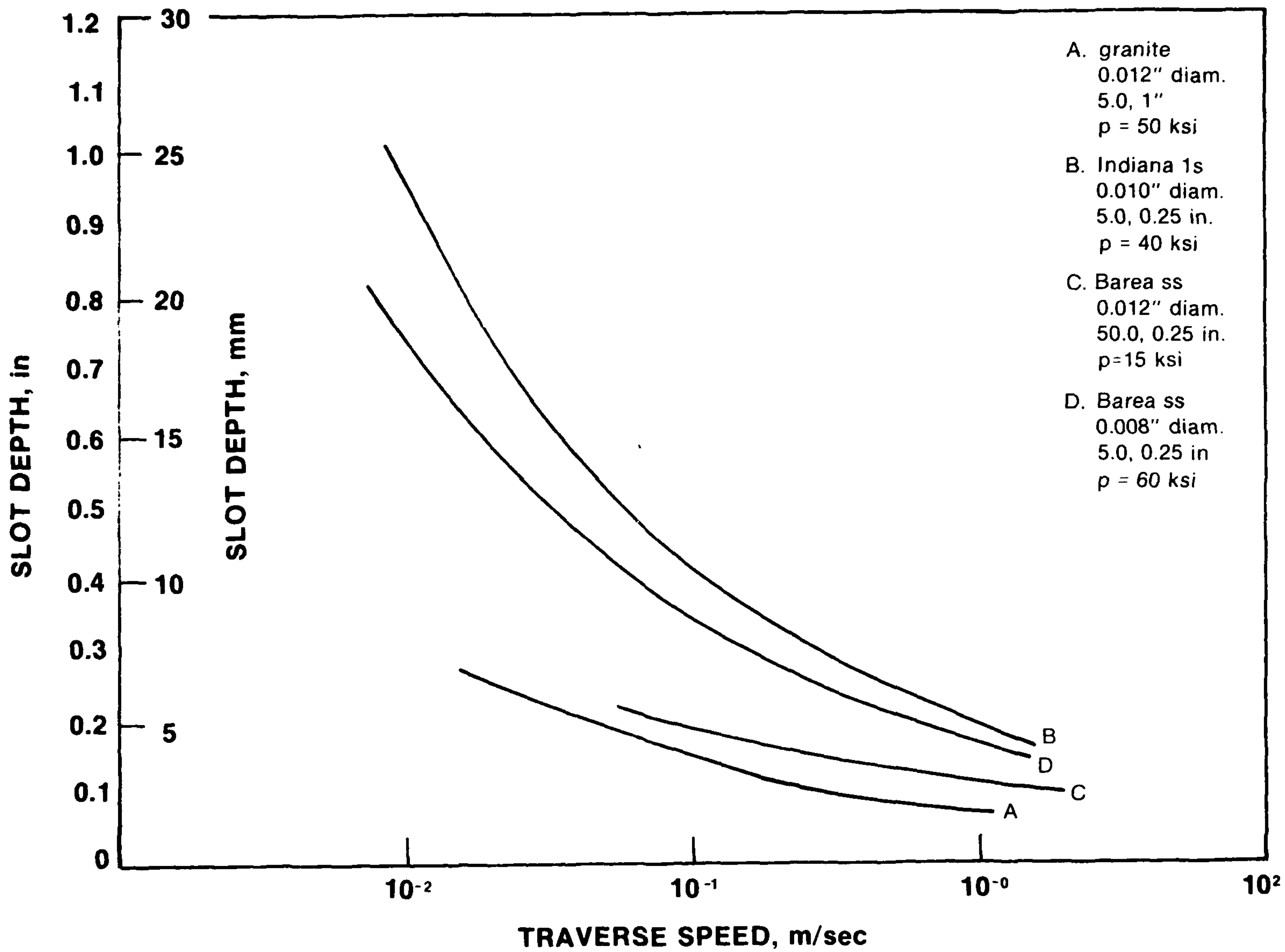

FIGURE 36 - Depth vs Traverse Speed (Ref. 3)

Hence, if a sandstone has good boreability, water jets could be utilized to reduce the power and cutter wear, or to increase the penetration rate. However, where the penetration rates are already high, the production of muck may exceed the capacity of the muck transport away from the face.

The use of water jet assisted boring has several advantages in both hard and soft rock, i.e., for either disc cutters for hard rock or picks for soft rocks.

Water jets have been employed in South Africa to assist in hard rock ploughing. Experimental work has also shown that water jet drills will bore small holes in sandstones very rapidly. The cuttability of rock depends upon several factors including hardness, porosity, mineral composition, grain binding, and other factors.

In summary, the applicability of water jet assisted boring depends upon the properties of the rock, the pressure and diameter of the jets, traversing speed, and the placement of the jet with respect to the cutters, discs, or picks. The number of water jets required must be determined by experimentation. The primary functions of the water jet for hard rock appears to be to clean the groove made by the cutter, remove partially broken chips, and to deepen the groove. For softer rock, the mechanisms may be similar, depending on factors in boring machine design, such as the shape of cutters, the cutter spacing, thrust, etc., but porosity is an important factor for sandstones.

Inasmuch as the only field tests that have been made with water jet assisted tunnel boring were made in granite, it is not possible to make an accurate prediction of the effects on boring penetration rates in other types of rock, which are less brittle, more easily crushed, and more susceptible to plastic flow. However, based upon boring penetration rates in

sandstones, it is logical to expect that water jet assist will increase rates of penetration significantly, with a comparable decrease in costs.

MIXED FACES

Tunnel boring in mixed faces is of interest because the stress waves generated in an attack could change the character of the rock, and rock near the surface at the point of egress may be weathered and consist of part soil and boulders. Hence, it will be desirable to design for an ETBM that will operate under the equivalent of mixed face conditions.

One such machine is reported as having been fabricated by the Robbins Co. and utilized in loose clays, soils, and siltstones (Ref. 9). The machine was equipped with a slotted roof shield to permit fore-poling, the supports being driven from inside the last ring beam. The extended roof shield gives protection for other support activities.

In 1972, Jarva, Inc., was considering the construction of a machine for a tunnel in clay and shale (Ref. 9). The bids called for continuous support with ribs and 100% lagging. The decision was made to use a mechanical shield with a rotary cutterhead which could: (1) obtain thrust from either temporary support or the tunnel bore, (2) have a flexible cutterhead to either overcut or undercut the shield, (3) use rotary disc cutters or drag bits, (4) have cutterhead rotation reversible, (5) have variable speed, (6) change cutters from inside the shield, and (7) allow erection of ribs and lagging continuously.

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9. Norman, N.E., 1972, "Mechanical Boring of a Mixed Face Tunnel," Proc. RETC, AIME, Chicago, Illinois.

ROCK PROPERTIES

Some of the basic first theoretical approximations and technical data related to tunnel boring in granite in Italy are useful in indicating some of the directions further research should take (Ref. 10).

In view of the variability of rock and the difficulty of preducting penetration rates from simply measured properties, fifteen different types of tests were used but did not prove to be dependable. These include the following, none of which had a good correlation with boreability (Ref. 10):

a. Compression test
b. Indirect tensile test
c. Shear test
d. Direct tensile test
e. Franklin test
f. Ultrasonic waves
g. Siebeck hardness
h. Mohs hardness
i. Punch test
j. Confined punch test
k. Rebound test
l. Drillability test
m. Wear test
n. Amster-Darry test
O. Protodiakonov test

The quantitative elements of rock breaking in tunnel boring are given as the geometry of the cutting head, the maximum available thrust (T max), the rotation speed of the head, the disc cutter type, the boring diameter (D), the power (W max), disc radius (R), and number of cutters (N).

The cutting edge of the disc is constantly changed by wear and a low value of R may increase penetration in hard rock because of the smaller length of the contact arc.

The load in each cutter is only approximately equal to T max/N. The energy consumed : that required to penetrate the rock (L) and that consumed in friction in the cutterhead (L'). For one revolution

10. Innaurato, N., R. Mancini, and S. Pelizza, 1975, "Consideration of Rock Boring Machines: Analysis of Italian Operations."

$$L = 0.55\ DT \sqrt{\frac{A}{R}} \tag{5}$$

and

$$L' = KT \tag{6}$$

where

A = advance in one revolution

K = dimensionless coefficient

The wear on tungsten carbide tipped discs is slight, and tool life may be related to bearing failure (Figure 37). In Italian experience, it was found that wear and bearing failure contribute almost equally to the reduction of cutter life in soft and medium rock, while in granite, wear accounted for 97% of cutter consumption. The petrographic and mechanical properties are of equal importance. Volumes of quartz and hard minerals give a crude but useful criterion.

For disc cutters used for granite, it was found that the rate of advance increased rapidly at about 0.8 critical thrust, and the relationship compared favorably with results of laboratory drilling tests (Figure 38). The efficiency of cutting increases from about 25% to 75% in this range.

The results of one of the most extensive studies of the relationship of conventional rock properties and geological conditions to boreability for prediction of advance rates (Ref. 11) utilized a "total hardness" factor.

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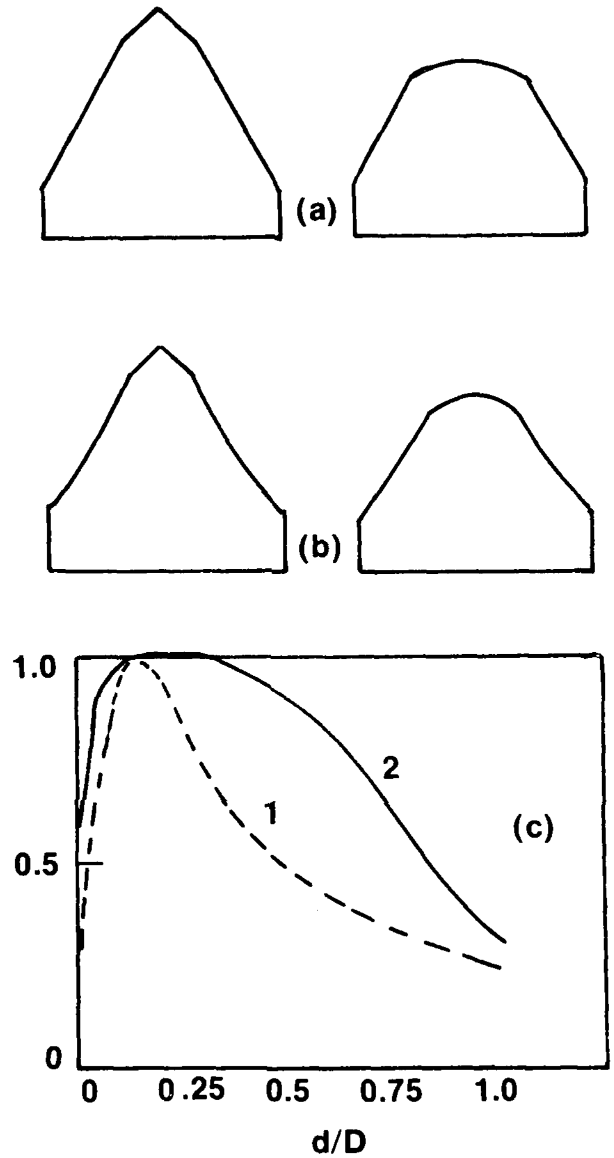
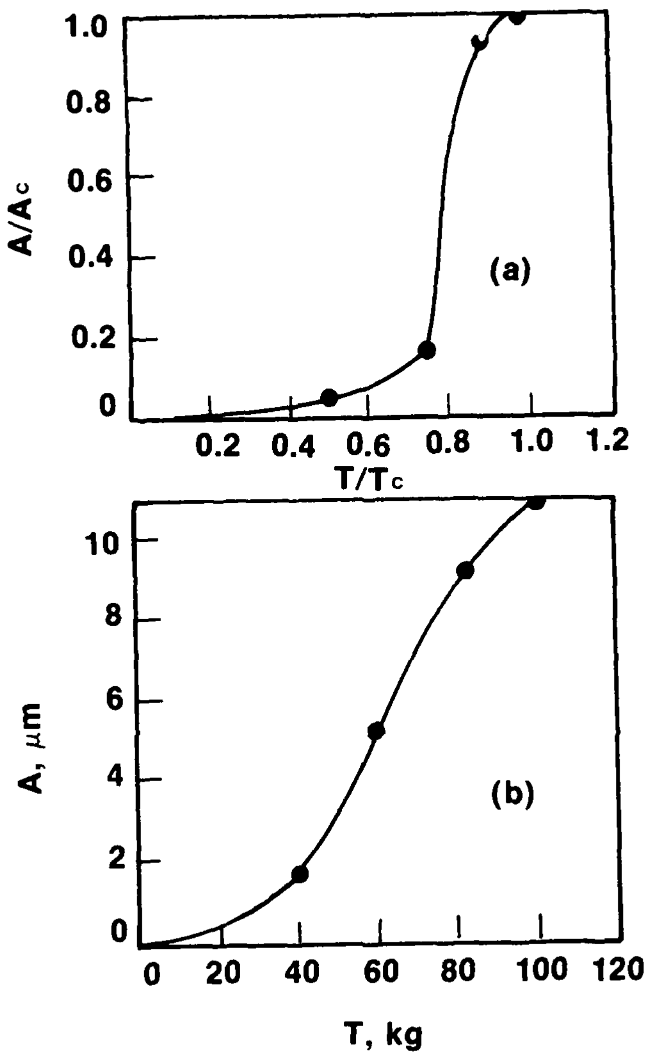
11. Tarkoy, P.J. and A.J. Hendron, Jr., 1975, "Rock Hardness Index Properties and Geotechnical Parameters for Predicting Tunnel Boring Machine Performances," Report (NSF, University of Illinois, Champaign-Urbana, Illinois.



Change in disc edge geometry due to wear: (a) new disc and worn disc (100 h of operation in granite), (b) new disc and worn disc (50 h of operation in extremely abrasive gneiss and quartzite), (c) disc life (arbitrary units) vs disc position on head expressed as ratio d/D (disc path diameter/head diameter) (note two minima at low d/D, due to small radius of path, and at high d/D, due to higher peripherical speed. Curve 1, granite; 2, extremely hard gneiss and quartzite).

FIGURE 37 - Wear Effects on Disc Edge Geometry



Advance per revolution vs thrust from tunnel boring operation in granite (a) data expressed with critical performance as unit, and for comparison, typical thrust/ penetration graph (b) obtained in laboratory drillability test on granite with 10-mm diameter carbide bit (Ref. 10)

FIGURE 38 - Advance Rates Per Revolution

The primary general factors recommended in Reference 11 for evaluation were (1) TBM compatibility with the geologic medium, (2) those affecting rate of penetration, (3) those affecting utilization, (4) cutter costs, and (5) economics (Table 9). Also, a TBM must be designed to be effective under different geologic conditions varying from bedded and jointed rock to solid, hard rock (Table 10). It was recommended in Reference 11 that a TBM be designed for compatibility with average geological conditions, for local adverse conditions, and to enhance overall efficiency. It would appear, however, that some overdesign is desirable with enough flexibility to cope with a wide range of conditions rather than just an average condition, particularly for the type of extensive tunneling considered in the DBM project.

Some of the design features of a TBM that may affect their performance (Table 11) are the design of the cutters and the cutterhead. Available data on machines employed on 13 projects (Table 12) indicate a wide variety in the features, although their effects on performance are not given. Every attempt should be made to design and construct the machine for best performance in the geologic medium expected.

The analyses in Reference 11 utilized experimental data on (1) rock strength tests, (2) rock hardness, including abrasion and rebound, (3) laboratory cutter tests, (4) punch penetration, (5) microbit drillability, and (6) experimental machines.

Correlations of penetration with unconfined compressive strength are low, although this property is often used as an index. When all of the data points from available sources were plotted, the coefficient of variation was 53%. Also, specific examples are given of granite and limestone which had the same compressive strength, but drastically different boreability.

TABLE 9

GEOTECHNICAL FACTORS AFFECTING TBM EFFICIENCY*

A. TBM capability to operate under expected geologic conditions

1. The TBM must be designed to perform under a wide range of conditions except in very hard rock or in very unstable rock.

B. Rate of penetration is determined by:

1. Type of rock and its boreability
2. Rock structure including faults, joints, alteration, etc.
3. Cutterhead diameter, rate of rotation and thrust
4. Cutter type, spacing and load

C. Utilization depends upon:

1. Support facilities
2. Utilities (ventilation, compressed air, power, etc.)
3. Muck transport capacity
4. Cutter changing efficiency
5. Cutterhead stability

D. Cutter costs

1. Wear due to abrasiveness, thrust, and rotation speed
2. Time for changing cutters
3. Cutter design and wearability (costs per ft or cu yd)

E. Rate of advance

1. Rate of penetration
2. Delays
    a. Cutter changing
    b. Muck transportation
    c. Repairs
    d. Cutting around curves
    e. Hard rock
    f. Fractured rock
    g. Water

F. Economics - total cost/ft

1. Capital cost and amortization
2. Labor
3. Repairs
4. Rate of advance
5. Costs due to unstable ground, water, etc.
6. Administrative
7. Overhead

* After Tarkoy & Hendron, 1975 (Ref. 11)

TABLE 10

GEOLOGICAL CONDITIONS REQUIRING SPECIFIC TBM DESIGN (Ref. 11)

Geological Conditions	Effect	TBM & System Design Requirements
Bedded & Jointed Rock	1. Joint block fallout will occur	1. Facilities for rock bolting directly behind cutterhead
	2. TBM grippers on the tunnel perimeter will cause fallout	2. Facilities for bolting ahead of grippers or for thrusting against support
	3. Heading instability	3. Vertical cutterhead with recessed cutters
Weak Rock (Underclay, Coal, Siltstone, Shale and Sandstone)	1. Intact rock will tend to fail, especially under deep cover	1. Full Support
	2. Support around the cutterhead will be required	2. Shield
	3. Inadequate reaction for the grippers will cause failure of intact wall rock	3. TBM designed to thrust against the liner
Squeezing Ground	1. Ground squeezing in at the face and cutterhead	1. TBM shield and full support; method of freeing shield
	2. Absorption of water and deterioration of gouge properties	2. Full immediate support
	3. Heading instability	3. Vertical cutterhead with recessed cutters
Slaking Ground	1. Slaking, continuing progressive deterioration of the tunnel perimeter	1. Facilities for full (360°) protection by epoxy resin paints, gunite, shotcrete, or full structural support
	2. Inadequate reaction for the grippers will cause failure of intact wall rock	2. TBM designed to thrust against the liner
Deep Cover	1. High ground loads	1. Shield and full support capacity
Faults & Shear Zones	1. Squeezing and blocky ground	1. Full support from the face
	2. Heavy ground loads	2. Support capacity
	3. Water inflow	3. Pumping capacity and grouting facilities
	4. Heading instability	4. Vertical cutterhead with recessed cutters
	5. Inadequate reaction for the grippers	5. TBM designed to thrust against the liner

TABLE 10 (Cont'd)

Geological Conditions	Effects	TBM & System Design Requirements
Groundwater	1. Flooding	1. Pumping and grouting capacity; protection of electrical equipment
	2. Deterioration and swelling of shales	2. Full surface protection
	3. Erosion of friable sandstones	3. Full surface protection
	4. Wet, hard to handle muck	4. Ribbed conveyors
	5. Muddy invert, poor trackage	5. Invert vacuum
Hard Rock	1. Frequent cutter changes	1. Facilities to provide fast movement of cutters to-and-from cutterhead and fast replacement

TABLE 11

OUTLINE OF TBM DESIGN FEATURES AND THEIR EFFECT ON PERFORMANCE
(Ref. 11)

Component	Various Design Features	Effect on Penetration Rate
Cutters	Type: hardened steel, tungsten carbide insert, solid body, single or multiple disk or tooth.	Variable, but also depends on rock hardness
	Diameter: 8 to 15-1/2 in. (20-39 cm), tapered or untapered	Larger diameters generally induces higher rates of penetration.
	Rolling Radius: small radius (18 in.; 46 cm), large radius (72 in.; 183 cm), or linear	Skidding may have both detrimental and beneficial but unknown effects on penetration.
	Loading: 5000 to 40,000 lbs of static load per cutting edge, dynamic load up to 70,000 lbs	Increased cutter and cutting edge load-enhances penetration rates.
Cutterhead	Shape: domed, flat	Domed heads have occasionally experienced reduced penetration as a result of face instability
	Rate of Revolution: depends on diameter and maximum allowable gauge cutter revolution	Revolution rate is directly proportional to penetration rate.
	Diameter:	Diameter limits cutterhead revolution rate.
	Drive: direct gear, air clutch, hydraulic	
	Thrust and Torque: requirements depend on diameter, depth of cutter penetration, cutter design, indirectly on rock hardness	Thrust is directly related to cutter penetration therefore torque is also a function of thrust.

TABLE 12

Summary of Rock-Machine Variables that Have Affected the Rate of Penetration for 13 Sites

Site	Manufacturer	Diameter, ft	Cutter Type	Cutter Diameter, in.	Cutting Edge Load, lbs	Cutterhead RPM	Rock
1	Lawrence	18.3	1D, 2D, 3D, 1DTC, 2DTC, 3DTC	15	27,000	Variable	Shale, siltstone, sandstone, orthoquartzite dolomitic limestone
North Branch Interceptor Sewer (North Heading), New York City	Jarva	8.5	3D, 3DTC+	6-9 tapered	11,000	- 10	Schist
North Branch Interceptor Sewer (South Heading), New York City	Jarva	11.0	3D, 3DTC+	6-9 tapered	10,000	- 9	Schist
Strawberry Aqueduct - Layout Tunnel, Utah	Robbins	12.92	1D	12	33,000	?	Shale, Siltstone, sandstone, conglomerate
Navajo Irrigation Project - Tunnels 3 & 3A New Mexico	Dresser	20.5	2D shallow	tapered 12-14	14,000	Variable	Sandstone and shale
Mt. Greenwood System Auxiliary Sewers No. 1 & 2, Chicago, Illinois	Robbins	10	1D	12	30,000	?	Dolomitic limestone
*Star Mine, Hecla Mining Co., Wallace, Idaho	Jarva	10	3D, 3DTC+	tapered 6-9	11,000	9 - 10	Quartzite
Austin Crosstown Interceptor Sewer (Shoal Creek to Bull Creek), Austin, Texas	Robbins	8.67-9.5	SD	12	31,000	8.2	Marl

See footnotes at end of table.

TABLE 12 (Cont'd.)

Site	Manufacturer	Diameter, ft	Cutter Type	Cutter Diameter, in.	Cutting Edge Load, lbs	Cutterhead RPM	Rock
*Queen Lane Raw Water Conduit, Philadelphia, Pennsylvania	Jarva	11.0	3D, 3DTC+	tapered 6-9	11,000	9 - 10	Schist
*Metropolitan Sanitary District of Greater Chicago, Illinois							
Lawrence & Harding Ave. Tunnels	Lawrence	13.7	1-2-3DTC	15	22,000	9	Dolomitic limestone
Calumet 18EA Contract	Jarva	16.83	3D+	6-9	11,000	9	Dolomitic limestone
SW 13A Sewer Contract	Robbins	13.83	1D	12	30,000		Dolomitic limestone
SW 17B Sewer Contract	Jarva	8.00	3D+	6-9	11,000		Dolomitic limestone
*11	Wirth	10.0	SBTC	8-9	<10,000	9	Granite, gneiss, schist
12	Robbins	19.0	1D	15.5	40,000	5	Gneiss, schist
*Lotschen Hydro Power Plant, Switzerland	Robbins Wirth		1D SBTC	12 8-9	30,000 <10,000		Schist Schist

*Poor Data

+Cutters track each other

1D - single disk
2D - double disk
3D - triple disk

TC - tungsten carbide insert
D - disk
MD - multiple disk, unknown rows
SB - solid body

The other properties listed above were analyzed and it was concluded that none of them showed good correlations with boreability. Reference 11 states, "It is impractical to test large slabs in the laboratory for each tunnel with the USBM apparatus to define variations in the rock. Obtaining a sufficient number of representative samples of sufficient size prior to excavation would be a monumental task with a high cost/benefit ratio." Other objections are stated: Laboratory-field relationships are unavailable, evaluations are time consuming, and results are not representative of variable conditions underground.

The CSM testing methods and results of experimentation show that it is possible to obtain large representative samples of rock and to evaluate their boreability, or to utilize smaller samples to give usable indices. Initial indications of the results of cutter tests using full scale cutters are that good correlations can be made with field boreability.

Various methods of testing rocks used by companies in attempts to predict TBM performance vary from full-scale cutting to punch tests and other methods (Table 13).

"Total hardness" was utilized by Tarkoy and Hendron (Ref. 11) and was proposed as the best method of predicting penetration rates from drill cores, but limitations are quite severe.

The total hardness is defined by:

$$H_T = H_R + H_A \tag{7}$$

where

H_T = total hardness

H_R = rebound hardness

H_A = abrasive hardness

TABLE 13

SUMMARY OF METHODS KNOWN TO BE USED BY TBM MANUFACTURERS FOR PREDICTING TBM PERFORMANCE (Ref. 11)

TBM Equipment Manufacturer	General Type of Testing Methods Used
Atlas-Copco	Full scale cutting on block (if available), also compressive strength, Mohs' hardness, nature of intergranular bonds, cleavage, and discontinuities (Lauber & Brodbeck, 1968).
Calweld	Microbit drillability (Ross & Hustrulid, 1972); Punch penetration (Handewith, 1975).
Dresser	Punch penetration and other tests (Morris, 1969).
Jarva	Reed Tool Company's tests (Fink, 1974); Rock hardness index properties described in this report.
Lawrence	Punch penetration (Handewith, 1970).
Reed	Punch penetration test (Fink, 1974); Percussive tests may also be used (Ross & Hustrulid, 1972).
Robbins	Strength, impact hardness, abrasion hardness, scratch hardness, Mohs' hardness, reaction to HCl (Robbins Co., 1974).

While correlations are fair for some rocks (Figure 39), the scatter is large and the rate of penetration is very insensitive to large changes of H_T. For most of the other plots of H_T vs penetration rate, the relations are so poorly defined that they are of little value. Also, no attempt was made in the correlations to introduce the effects of the type of cutter used, the thrust, the speed of cutting, or other pertinent factors.

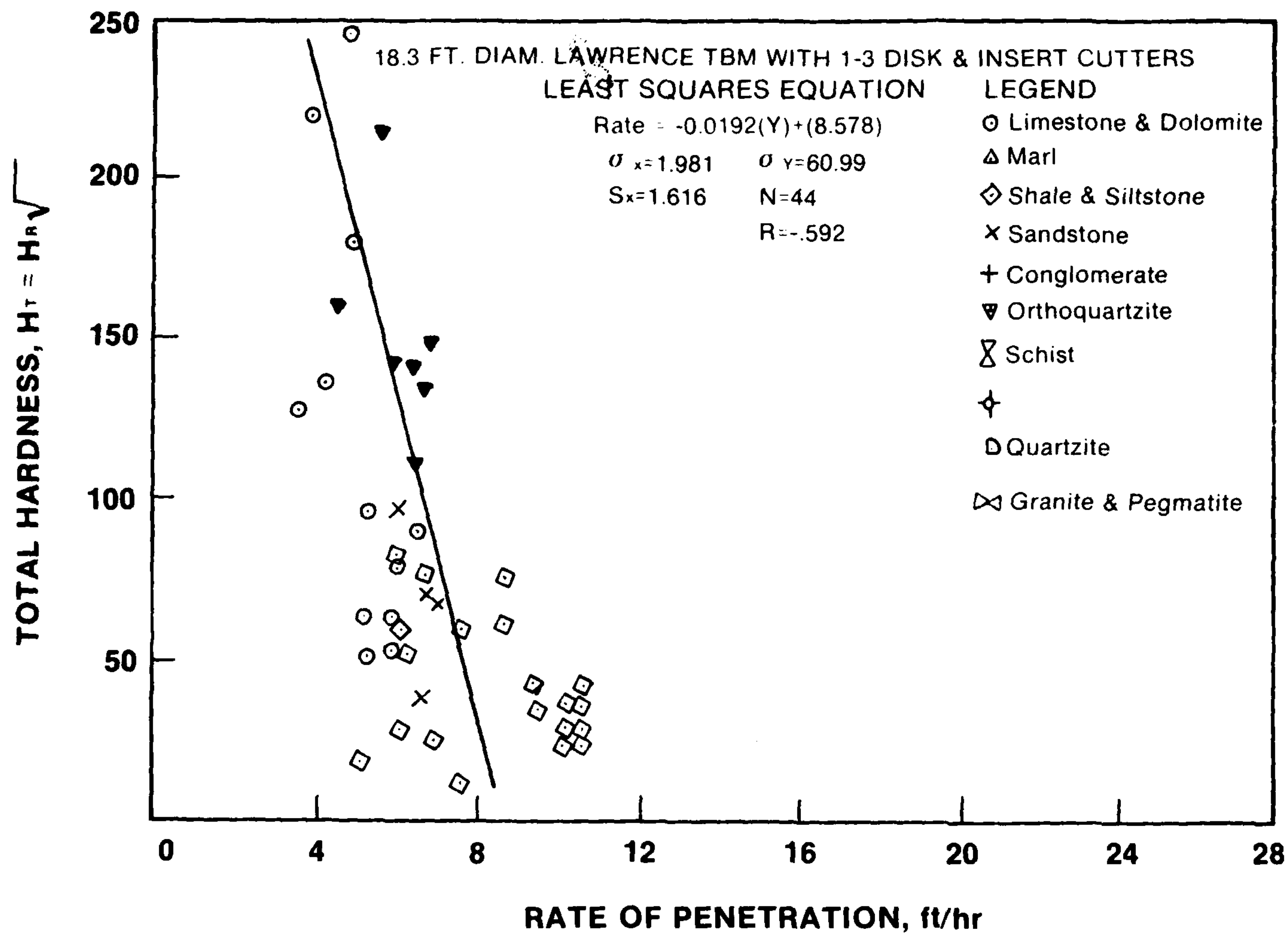


FIGURE 39 - Plot of Data and Results of Statistical Analyses from Site 1, for Penetration Rates as a Function of Total Hardness (Ref. 11)

TUNNELING COSTS

In 1968 (Ref. 2), there were insufficient data to permit firm conclusions on the relative costs of tunnel boring, because (a) cost figures are not made available because of competitive bidding, (b) cost values are not clearly defined, (c) variation of geologic conditions reduces significance of comparisons, and (d) decisions for a choice of method is based on the economics of a particular job.

Cost trends indicated by available values indicate that labor is one of the high costs (Figure 40). For drill and blast, the costs increase rapidly with tunnel diameter and inflation (Figure 41). Costs also vary widely with the properties and conditions of the rock (Figure 42) (Tables 15 & 16).

Relative driving costs for drill and blast and machine excavation (Tables 14 & 15) include those for machines, capital investment, power, cutters, labor, and maintenance. The total cost per cubic foot excavated is favorable, but the bidding cost on drill and blast is much higher. Equipment costs (Table 15) are about three times greater for an 8-ft diameter machine than for drill and blast.

The smaller the tunnel, the greater the length must be if the whole of the machine cost is to be paid off during a given project.

The following cases illustrate savings from use of tunnel boring machines.:

Chicago Metropolitan Sewer Board. Cut labor costs 8 to 12%, construction time by two-thirds, total cost by 40%.

Boyle Bros. One year's delay in manufacturing time was made up in five months. Time available was 80%, reliability was good. (Tunnel in sandstone).

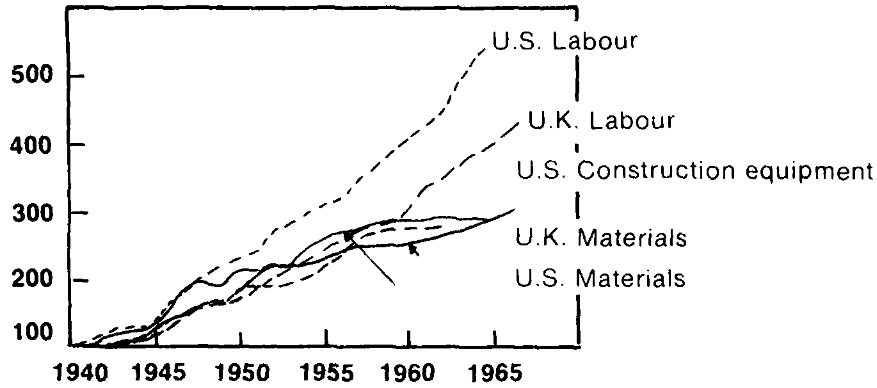


FIGURE 40 - U.K. and U.S.A. Cost Indices (1940-1966) (Ref. 2)

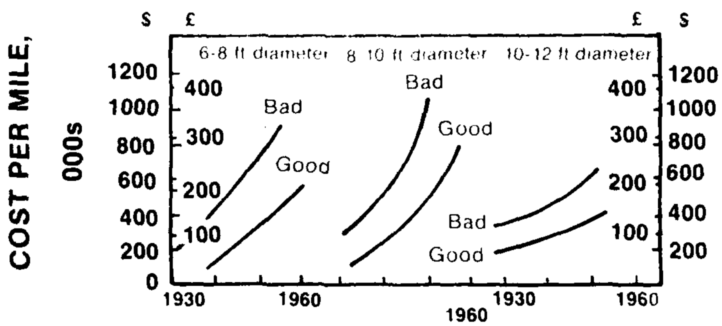


FIGURE 41 - Cost Trends for Conventional Tunnels (1961), after U.S. Bureau of Reclamation (Ref. 2)

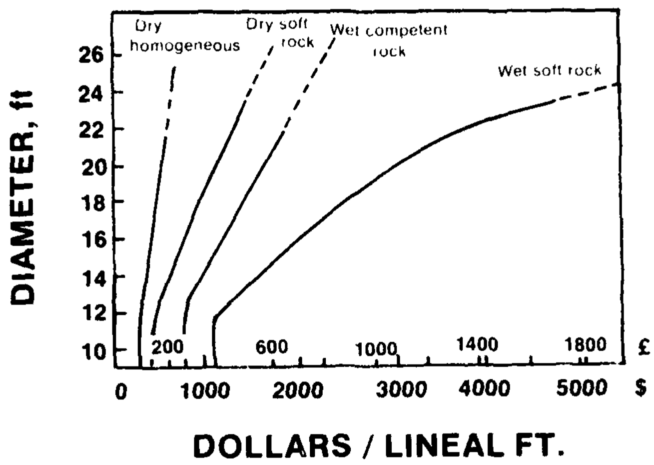


FIGURE 42 - Estimated Costs (Basic) of Tunnel Excavation (1964) (Ref. 2)

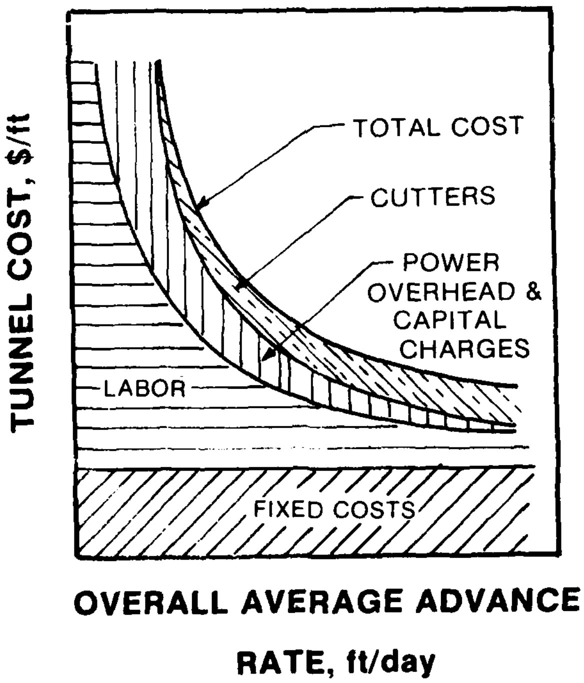


FIGURE 43 - The Cost of Machine-Bored Tunnels in Relation to the Overall Average Advance Rate (Ref. 12)

TABLE 14

TUNNEL DRIVAGE COSTS, £/FT^3 (Ref. 2)

	Conven-tional	Conven-tional Average	Actual Costs Jarva	Habeg-ger	Law-rence	Cald-weld	Rob-bins	Tender Estimates Caldweld	Conven-tional
Labour	0.20	0.39	0.07	0.07	0.05	0.16	0.17		
Tunnel equipme t	0.06	0.01	0.29	0.09	0.10	0.05	0.04	Contractor's winning tender cost with machine	Winning contractor's tender cost with explosives
Power	0.02	0.02	0.02	0.01	0.03	0.02	0.18		
Consumables (explosives, drills, cutters, etc.)	0.08	0.20	0.07	0.04	0.23	0.09			
Maintenance and repair	0.01	0.01	0.03	0.11	0.03	See labour			
Miscellaneous	0.04	0.04	0.04	0.04	0.04	0.04	0.04		
Total (operating)	0.41	0.67	0.52	0.36	0.48	0.36	0.33	0.47	0.83
Temporary support	----	0.05	----	----	0.04	----	----	----	----
Concrete lining	----	0.33	----	----	0.22	----	----	0.17	0.38
Total (tunnel)	----	1.05	----	----	0.74	----	----	----	----
Tunnel diameter	8 ft	12 ft	8 ft	11'-6"	----	15'-11"	16'-1"	25'-9"	11'-6"
Tunnel length	1000 ft	10,000 ft	10,000 ft	16,500'	----	6900 ft	14,600'	18,300'	17,000'

TABLE 15

EQUIPMENT COSTS (8-ft DIAMETER TUNNEL) (Ref. 2)

Explosives Method	Pounds Sterling	Machine Method	Pounds Sterling
3 Holman Silver Three Drills	550	8-ft tunneling machine	118,000
3 Airlegs		50-ft bridge conveyor	2,300
1 Saltzgitter rocker shovel	5,200	Dust extractor	700
1 Saltzgitter bunker train	25,000	1 4-ton diesel locomotive	3,800
3 auxiliary fans	750	24 2-yd^3 tipping wagons	4,800
2 water pumps	600	2 auxiliary fans	500
1 compressor, 300 ft^3/min	1,000	2 water pumps	600
1 4-ton diesel locomotive	3,800	700-yd trailing cable	4,200
		Electric drill	100
	36,900		135,000

Engineering and Mining Journal. In addition to excavation savings in a 12-ft diameter tunnel, 1 yd^3 of concrete per foot of tunnel saved.

Homer Mine. Machines faster, lower cost. Cost of machine recovered by labor savings in one year.

Richmond Water Board. Cost of explosives for 5 miles of 12-ft drain tunnel was equal to cost of machine.

Tasmania. Enlarging railway tunnel cost only 56,000 £ vs 16,000 £ by drill and blast.

Orange River Project. Savings in concrete in 17 miles of tunnel would buy two machines compared to drill and blast.

Navajo Tunnel. Labor and operating costs lower, less concrete and temporary support required, driving time reduced by one half.

The conclusion was drawn that tunneling machines could be justified (1968) for smaller diameter tunnels of sufficient length. The lower limit of rock strength was determined by self-support, and the upper limit was determined by the rate of wear on the cutters.

In a later analysis of tunnel boring costs, Robbins (Ref. 12) states that the most serious problems are unexpected variations in tunneling conditions. The number of tunnels being bored here and abroad has increased because of decreased unit costs and greater speed.

Tunneling costs consist of fixed and variable costs. Fixed costs include equipment amortization, job-site installation, tunnel services, such as track, ventilation lines, power cable, water and compressed air lines, lighting, etc. If ground conditions are consistent, tunnel support is a fixed cost.

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12. Robbins, R.S., 1970, "Development Trends in Tunnel Boring Machines for Hard Rock Application," 1st U.S.-Sweden Underground Workshop, Stockholm, December 1976.

Variable costs include labor, power, overhead, and cutter costs. Costs are also related to the advance rate (Figures 43 & 44), factors which have a major effect on the advance rate also affect tunnel costs.

The factors which have a serious effect on advance rate are:

(a) Unexpected large variations in tunneling conditions such as fault zones, changes in rock structures, hardness, etc.

(b) Variations in rock properties which affect penetration rate and downtime.

(c) Major breakdowns which result from manufacturing problems or operating problems, such as erratic steering, advancing with worn out cutters, and poor maintenance.

Cutter cost is a major item, with guaranties for their operation sometimes being made where the geological conditions are well known. Such costs usually vary as the square of the tunnel diameter, and approximately in proportion to the compressive strength of the rock, and inversely with the penetration rate. The travel and wear are proportional to the rotation and the radial distance to the cutter. Cutter performance also depends upon the spacing, edge geometry, and other factors. Cutter penetration rate for a given rock machine combination is greatest above a critical value of thrust (Figure 44). Robbins also gives penetration rates based upon the compressive strength of rock, but these can be employed only as approximations.

Robbins (Ref. 13) has also described some of the important trends in TBM applications for hard rock. Because of a continuous rate of improvement in TBM technology, TBMs are now being used for hard rock that would have been excavated by blasting a few years ago. Additional improvements are expected in the next few years.

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13. Robbins, R.J., 1970, "Economic Factors in Tunnel Boring," South African Tunneling Conference, Johannesburg.

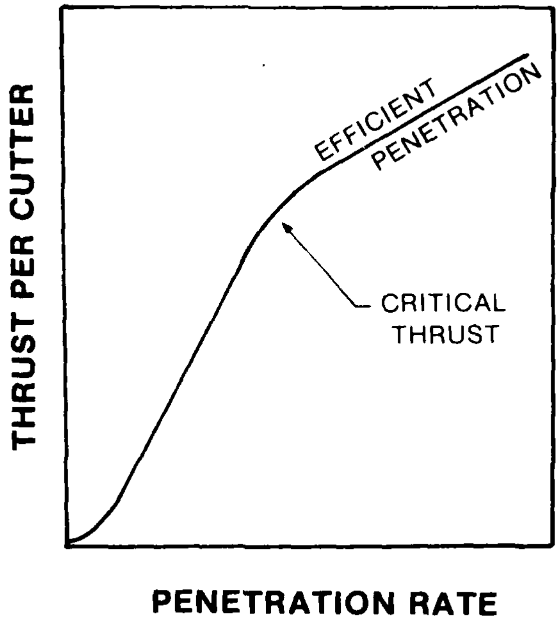

FIGURE 44 - Typical Cutter Penetration (Ref. 12)

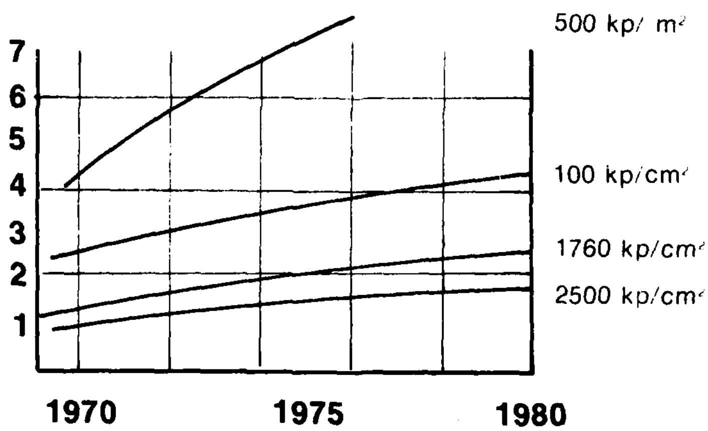

FIGURE 45 - Penetration Rate vs Time Showing Effect of Rock Strength at 3.7 m ϕ

Too little research has been done, the most important advances having been made as a result of tunneling experience. More research monies are being made available by government and industry and even small cost reductions reap real benefits in the long run.

The major barriers to progress in hard rock are the rock hardness, machine design limitations, and bad ground. Hardness in rock presents resistance to crushing and penetration, which must be overcome by using new metals or other materials. Machine component limitations are in cutter design and wear in relation to rock properties. Fractures, joints, and their geometry and spacing play a major roles in addition to the properties of intact rock.

Harder rocks are being bored every year, cutter costs per volume excavated are decreasing (Figure 45) but all of the curves are flattened out toward a critical point of diminishing returns. The higher cost of raise boring machine (RBM) cutters is due to the relative instability of the RBM. Cutter costs decrease with higher rates of advance (Figures 46 & 47) which are affected by both tunnel diameter and rock strength.

For a bad ground, such as that found in fault zones, Reference 12 states that, "The most important development frontier is the machine for very bad ground which can also handle hard rock. Much progress has been made in this direction in the past five years." One such machine was developed for a hydroelectric tunnel in Italy. It was designed with a spoke-type cutterhead with a double telescoping shield around the machine. This permits steering as well as protection from rock falls. However, large boulders falling against the face of the cutterhead could not be handled. A rotating face support was added, which permitted the machine to advance through bad ground. Equipment is also being developed to bore small tunnels, and noncircular boring machines have been developed by the

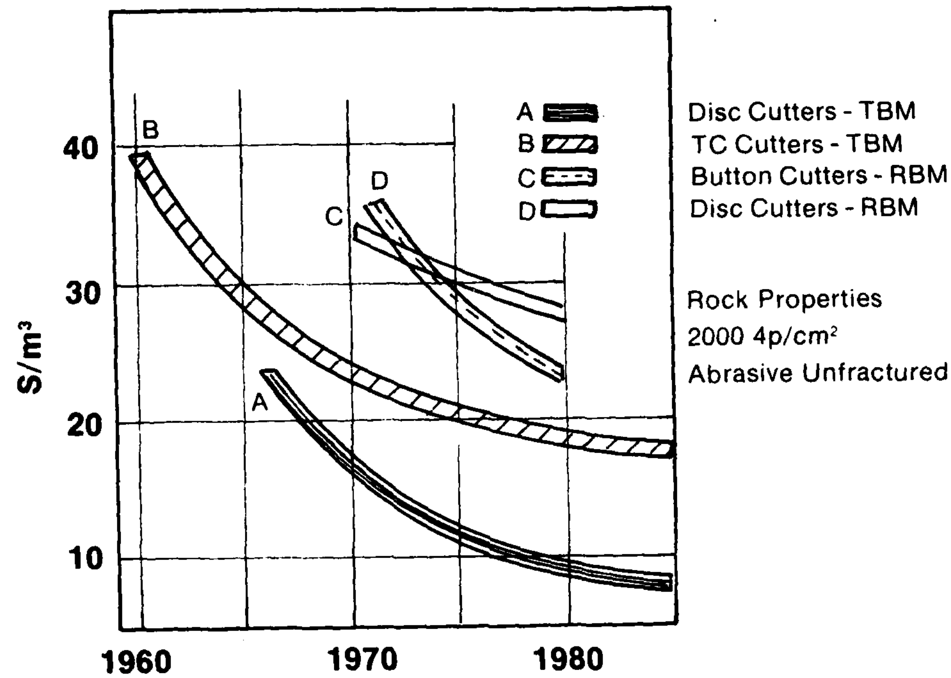

FIGURE 46 - Cutter Costs (1976) vs Time

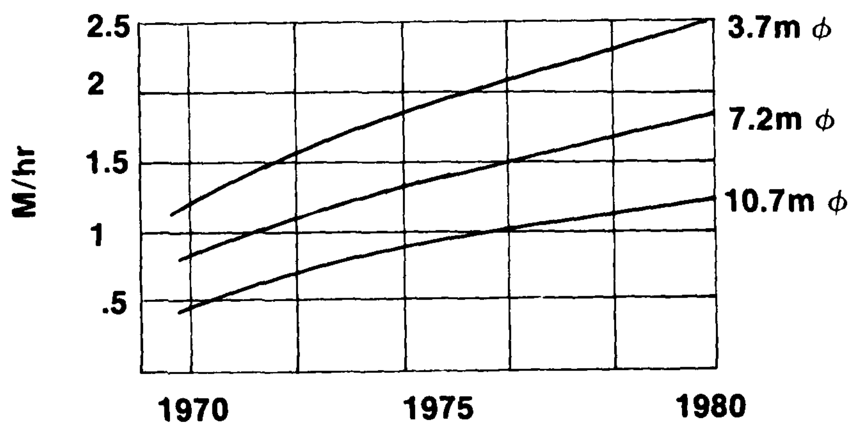

FIGURE 47 - Penetration Rate vs Time; Showing Effect of Tunnel Size in Rock of 1760 kp/cm^2

Atlas-Copco Co. A similar machine built by Robbins cuts a 1.5 by 2.1 meter face using rolling disc cutters, which are mounted on two arms which swing up and down across the face.

PREDICTION OF FIELD BORING RATES

The procedures and methods of rock testing necessary for providing the tunnel boring industry with a simple, reliable boreability prediction tool has been the major goal of recent and current boreability studies at the Colorado School of Mines. As a result of extensive laboratory and field investigations, two methods of successfully predicting field boring rates have been devised. These methods were designed to make measurements of those properties of rocks which can be employed for prediction as revealed by the proper types of tests. This necessarily requires a test that simulates the conditions existing in tunnel boring.

Laboratory Equipment, Instrumentation and Testing Procedure

Two linear rock cutting machines, one small and one large, are available for performing laboratory boreability studies. The small cutting machine, which is an extensively modified milling machine, permits testing at reduced cutter loads and penetrations on small rock samples. The machine requires minimum preparation effort, thus enabling one to generate extensive cutting data in a short time. It can accommodate small rock samples, as small as those obtained from exploration drill cores. This machine is primarily used for running preliminary tests to aid in the design of testing programs for large machine testing.

The large linear cutting machine, which was designed and built at the Colorado School of Mines (Ref. 14), can simulate field boring conditions and provides the following capabilities:

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14. Hustrulid, W., 1970-71, "Experimental and Theoretical Study of Tunnel Boring by Machine with Emphasis on Boreability Prediction and Machine Design," ARPA Contract with Colorado School of Mines, Golden, Colorado.

1. Can use various sizes and types of field cutters

2. Can apply manufacturer's suggested allowable cutter loads

3. Has maximum deflection of 0.01 in. at a cutter load of 25,000 lb

4. Capable of higher loads (up to 100,000 lbs) safely, but with a corresponding increase in deflection

5. Capable of being operated both in constant penetration and constant force modes

6. Full range of cutting speeds similar to those found on most tunnel boring machines

7. Can be set to cut desired depth equivalent to those of boring machines

8. Lateral confining pressures can be applied to the specimen, simulating underground loading and confinement

9. Required spacing of cuts is easily set by lateral movement of the specimen

The instrumentation includes a triaxial load cell capable of resolving the load on the cutter into its three mutually perpendicular components and high speed digital integrators for recording of forces. Units are also available for monitoring the peak values of all force components. Hard-copy records of the cutter forces are provided by a time-base strip chart recorder, permitting visual observation of the behavior.

The overall instrumentation system measures the average values of the three cutter force components (vertical, rolling, and side) along with peak recordings. The dynamic behavior of cutter forces and their frequency can be obtained from analysis of the hard copy records (graphs).

Sample blocks of maximum dimension 3 ft^2 by 2 ft high are used for the large machine testing. Only one surface of the sample is required to be reasonably flat and this surface is chosen to be the cutting surface. The sample blocks are cast in concrete, placed in the machine rock holder box, and confinement is applied to prevent splitting during testing.

The testing procedure involves setting the cutter at the required level of penetration and then traversing it over the rock surface and measuring the forces acting on the cutter. Each test consists of making several passes over the rock surface, with each pass consisting of several cuts taken at a fixed spacing. Cutting is begun with a smooth rock surface, but data for the first two or three passes over the whole surface are discarded. These cuts condition the rock and create a rock surface similar to that found on a tunnel boring face. The cutting velocity for all tests is held constant at ten inches per second. This choice is based on earlier experimental results in which the cutting velocity was found not to affect cutter forces in the range above 5 to 10 in/sec.

Other Equipment:

Sample Preparation Equipment. This includes coring machine, diamond saws, surface grinders and rock splitters, and equipment for on site sample acquisition.

Physical Property Testing Equipment. Soft and stiff testing machines, including a one million pound capacity electronic servo-controlled stiff testing machine, are available for physical property tests, and equipment for indentation testing, abrasivity determination, and sieve analysis.

Data Acquisition and Processing Equipment. Data processing equipment includes high-speed multi-channel integrators, peak detection units, a programmable calculator with a 500 k storage unit, a PDP-10 time-sharing computer, magnetic tape recorders, and printers.

Data and Analysis

A large linear cutting machine meets the need for a boreability prediction tool. Since this machine has the capability of closely simulating field cutter loads and penetrations, it can provide the necessary

information for efficient machine operation and expected penetration rates for given machine operational parameters. With this equipment, rock samples from a field boring site were cut with the same type of cutter as was being used in the field and a good correlation was found between the field and laboratory penetration rates, as shown in Figure 48.

Secondly, through an analytical approach, predictor equations have been developed with the objective of providing estimates of field boring rates. The equations were initially developed for disc roller cutters because of their simple geometry and wide use in mechanical tunnel boring. Following is a summary of these equations together with the nomenclature involved:

$$VF = D^{1/2}p^{3/2} \left[\frac{4}{3} C + 2\tau\left(\frac{s}{p} - 2 \tan \frac{\alpha}{2}\right) \tan \frac{\alpha}{2} \right] \tag{8}$$

and

$$RF = \left[CP^2 + \frac{4\tau\phi(s - 2p \tan \frac{\alpha}{2})}{D(\phi - \sin\phi \cos\phi)} \right] \tan \frac{\alpha}{2} \tag{9}$$

where

VF = vertical force on the cutter (lbs)

RF = rolling force on the cutter (lbs)

C = rock uniaxial compressive strength (psi)

τ = rock unconfined shear strength (psi)

D = cutter diameter (in.)

α = cutter included edge angle (degrees)

s = spacing of cuts (in.)

p = cutter penetration (in.)

$\phi = \cos^{-1} [(R - p)/R]$, where R = cutter radius (in.)

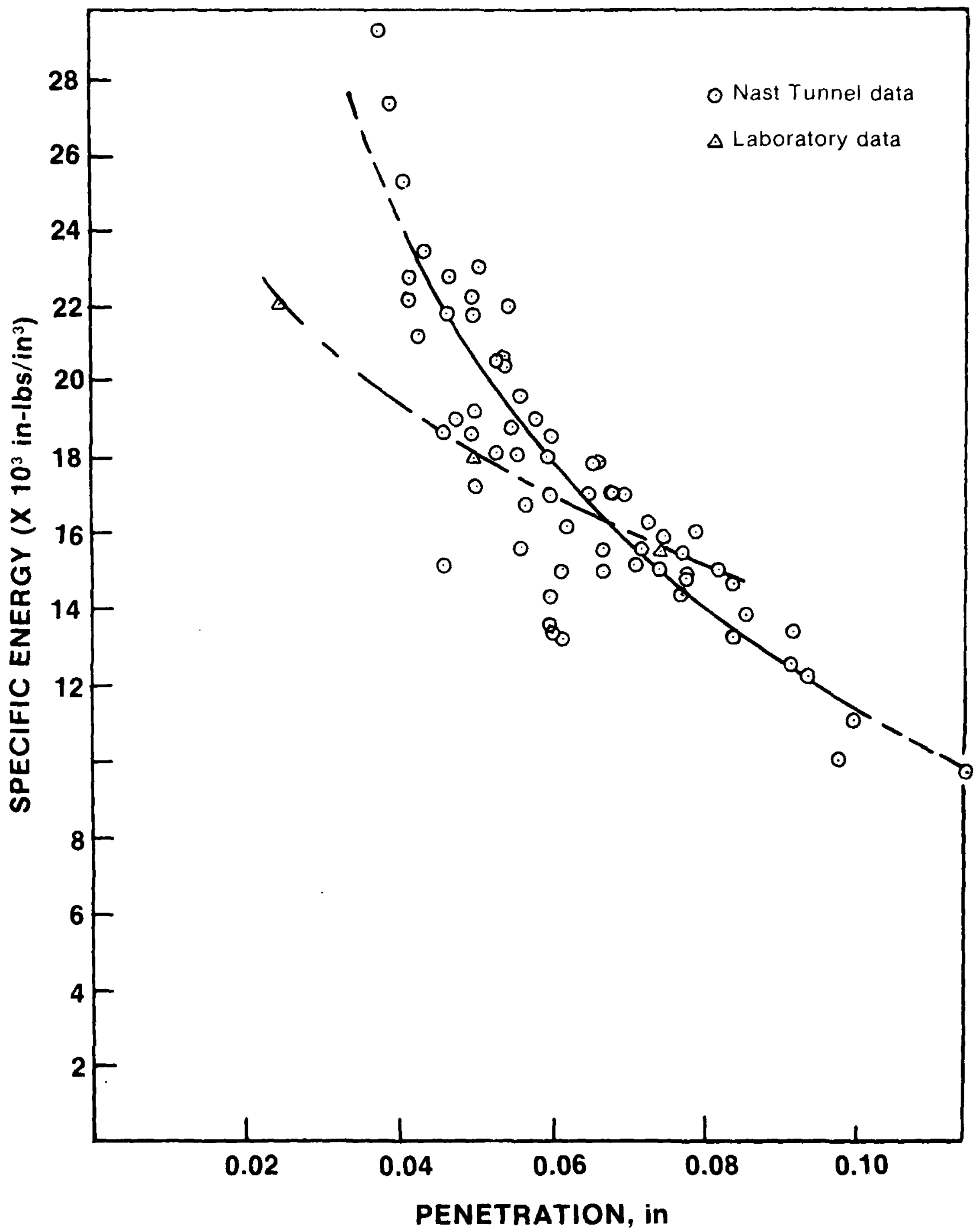


FIGURE 48 - Specific Energy vs Penetration for Laboratory and Field Cutting of Nast Tunnel Granite

As presented, the above equations may be used to calculate the vertical and rolling forces on a disc cutter of given geometry, penetration, and spacing for required rock properties. If penetration at a given cutter load is the unknown quantity to be determined, then the equations can be solved for the value of penetration. To facilitate calculations, these equations can be solved using any programmable pocket calculators.

Since most tunnel boring machines operate with cutters in some stage of wear, the developed predictor equations were modified to consider the effect of wear on disc cutter performance. Based on a survey of field cutter wear patterns and discussions with cutter manufacturers, a toroidal wear surface was chosen to represent the edge geometry of worn disc cutters. The equations for sharp disc cutters were modified (for a toroidal wear surface), resulting in the following set of equations for estimating the forces on worn disc cutters.

For $p < r\left(1 - \sin\frac{\alpha}{2}\right)$

$$VF = D^{1/2}p^{3/2}\left[\frac{4}{3}cd + 2\tau\left(s - 2d\right)\left(\frac{\gamma - \sin\gamma\cos\gamma}{(1 - \cos\gamma)^2}\right)\right] \tag{10}$$

where

$d = (2rp - p^2)^{1/2}$

For $p > r\left(1 - \sin\frac{\alpha}{2}\right)$

$$VF = D^{1/2}p^{3/2}\left[\frac{4}{3}cd + 2\tau(s - 2d)Z\right] \tag{11}$$

where

$d = (p + TL)\tan\frac{\alpha}{2}$

and

$$Z = \frac{\left(r\cos\frac{\alpha}{2} + d\right)\left(p - TL\sin\frac{\alpha}{2}\right) + r^2\left(\gamma - \sin\gamma\cos\gamma\right)}{p^2} \tag{12}$$

Besides the previously defined terms, the new terms entering into the above equations are:

r = radius of wear surface (in.)

TL = tip (radius) loss due to wear (in.)

$\gamma = \pi/2 - \alpha/2$ (degrees)

The rolling force is then given as:

$$RF = VF \times CC \tag{13}$$

where

$$CC = \frac{(1 - \cos\gamma)^2}{\gamma - \sin\gamma \cos\gamma}$$

The developed predictor equations for sharp and dull disc cutters were found to successfully predict the laboratory cutting results. They also closely predicted the instantaneous rate of penetration and horsepower requirements of tunnel boring machines presently in operation in dolomitic limestone in Chicago, Illinois (Table 16). The predictor equations are now being used or verified by major tunneling equipment manufacturing companies including Jarva, Inc., The Robbins Co., Dresser, and Ingersol-Rand.

TABLE 16

COMPARISON OF FIELD DATA TO PREDICTED DATA (Ref. 7)

Machine	Collected Data				Derived Data			Predicted Results for the Same Machine Thrust	
	+Effective Thrust Pressure (psi)	Motor Amperage (amperes)	R.O.P. in/3 min	Station	Thrust (lbs)	hp	R.O.P. (ft/hr)	hp	R.O.P. (ft/hr)
MK 30-3001	2,000	95	3.37	269+41	1,508,300	1,263	5.6	1,199	5.3
MK 30-3001	2,500	125	4.62	269+41	1,885,300	1,740	7.7	1,735	7.4
MK 30-3001	2,700	130	4.68	266+27	2,036,199	1,815	7.8	1,968	8.3
MK 30-3001	2,650	140	4.5	258+73	1,997,989	1,965	7.5	1,907	8.1
MK 12-1307	1,250	165-169	5.7-6.3	Many	795,000	585-600	9.5-10.5	592	10.4

+Effective pressure is actual pressure minus the pressure required to move TBM cutterhead forward under no load.

	MK 30-3001	MK 12-1307
Average rock unconfined compressive strength during tests	11,875 psi	17,925 psi
Average rock tensile strength during tests	1,410 psi	2,010 psi
Estimated rock shear strength during tests	1,900 psi	2,250 psi

COMPUTING COSTS FOR TUNNELING IN ROCK (COSTUN)

At the conceptual and planning stages of major tunneling projects (Ref. 15), engineers and planners usually require dependable estimated costs for evaluation of alternative routes, selection of construction methods, establishment of budgets, and verification of estimates. Sources of cost data include: manually calculated estimates for each proposed tunnel which may be a costly and time-consuming process, use of existing computer programs which is inconvenient for many users who do not have both the computer and the software immediately at hand, or cost curves calculated by means of computer program. The latter are convenient and, despite the requirement for updating as costs escalate and new technology emerges, serve a useful purpose. A set of cost curves is presented below from which up-to-date costs may be read for tunnels excavated by either drill and blast or machine boring methods. The costs were computed with a program (COSTUN) in which the logic and methodology were modeled after manual methods of cost estimating. The program has been calibrated against a number of constructed tunnels and found to be well within the range of accuracy expected for conceptual cost estimates.

The computer program COSTUN, on which these costs are based, was developed under a Harza Engineering Co. contract with the Department of Transportation and is available from the National Technical Information Service. The program was described in a paper in the 1974 RETC Proceedings (Ref. 15). The program is easy to use, but requires voluminous data relating to tunnel geometry, site conditions, and other parameters. The limited use of the program in its three-year existence is believed to stem

15. Wheby, F.T., 1975, "Parameter Estimates of Costs for Tunneling Rock," Tunneling Technology Newsletter, U.S. National Committee on Tunneling Technology, NAS/NAE, Washington, D.C.

not only from the difficulties of data-gathering and operation but also because calculated results cannot be readily checked.

The above difficulties can be largely avoided by the use of cost curves whose validity can be subjectively judged, and the accuracy can be verified as cost data for newly constructed tunnels become available. Curves have the additional advantage of permitting ready evaluation of the sensitivity of parameters to tunnel costs, though the absolute magnitudes of these costs may be questioned. The curves are not intended to supplant estimates of probable cost made by conventional methods. Manual estimates should continue to be made for many tunnels in the final stages of planning and feasibility analyses, and always for final design because values from the COSTUN program cannot reflect all the individual details of given projects.

If no value is given for one of these optional inputs, the computer will select a value based on built-in criteria. Other data, such as characteristics of the ground through which the tunnel is to be driven, are required inputs.

Most of the important parameters are familiar to planners and engineers. A possible exception is RQD (Rock Quality Designation), the parameter used for classifying the rock according to its intensity of jointing (Table 17), which can be considered to be a modified measure of core recovery.

TABLE 17

ROCK QUALITY DESIGNATION (RQD)

RQD	Description
90-100	Excellent
75-90	Good
50-75	Fair
25-50	Poor

Of the tunnel shapes available for selection for drill and blast excavation (Figure 49), the circular shape is the only permissible one for machine-bored tunnels.

Figure 49. Alternative Tunnel Shapes for Drill and Blast Excavation

The costs for drilled and blasted tunnels are given for comparison. The variable inputs for generating the curves for D & B are as follows:

RQD: 40, 60, 80 and 100%

Rock Strength: 5, 10, 20 and 40 ksi (3.5, 7, 14 and 28 x 10 kN/m^2)

Tunnel Wideth (B): 10, 20, 30 and 40 ft (3, 6, 9 and 12 m)

Water Inflow at Face: 0 and 200 gal/min (0 and 0.8 m^3/min)

Lining: Not lined and lined

Muck Haulage: train for 10- and 20-ft (3 and 6 m) tunnels; train for 30- and 40-ft (9 and 12 m) tunnels

Points for the curves were calculated by entering into the COSTUN program values for the parameters (size, rock quality, etc.) that affect tunnel costs. Those parameters that are relatively unimportant were input as single fixed values. Others that are more important, to which costs are more sensitive, were input as variables with several specific values within the expected range.

For example, the cost of tunneling appears to be only mildly affected by its geographic location (provided one ignores, for example, the enormously high costs generally found in the environs of New York City. Therefore, in generating the cost curves, geographic factors relating to a

single specific location (Chicago) were used. On the other hand, tunnel costs are highly sensitive to the size of the tunnel and the geologic structure through which it is driven. For that reason, these parameters were given several selected values, and the costs plotted as functions of size and geologic conditions.

A separate cost computation was made for each combination of all values of input parameters. The curves presented below required 384 runs of the program.

The COSTUN program relationships and logic represent as closely as possible a direct simulation of the mental processes of tunnel designers and cost estimators. The program does not utilize mathematics of probabilistic concepts beyond those that would normally be utilized in a manual design or estimate, but the output has been verified and calibrated against a number of tunneling projects.

The program also contains built-in designs for lining and support, and the user has some control over the way these designs are applied to a particular tunnel. For example, the lining may be specified as either shotcrete or cast-in-place concrete. Other inputs are optional, that is, if the user wishes to specify a method or value, he may do so.

Fixed value parameters are:

Groundwater Elevation: 50 ft (15 m) above tunnel invert

Labor, Equipment and Material Cost Indexes: for Chicago at year end 1975

Tunnel Length: 10,000 ft (3,050 m)

Lining Type: concrete

Lining Designed to be Watertight: yes

The costs include all direct costs of tunneling, including contractors' overhead costs and profit, but do not include costs of portals and shafts, permanent lighting and ventilation, roadways, and architectural finishes,

or the aboveground costs such as for utility and roadway relocations, acquisitions of rights-of-way, traffic detours, and environmental protection.

The curves should not be used for small projects (less than about $1,000,000 in tunneling), and should be adjusted for tunnels whose lengths differ materially from the input length of 10,000 ft (3,050 m). Usually, costs per foot of tunnel will decrease somewhat with increasing tunnel length.

To use the curves for costs of drilled and blasted tunnels, one estimates the cost of an unlined tunnel being driven through a dry formation by entering Figure 50 with the nominal clear dimension (B) of the tunnel and reads off the cost at the applicable RQD and rock strength. This cost includes costs of all of the usual operations in driving unlined tunnels in dry headings: excavation (including overbreak), mucking, supports, and ventilation.

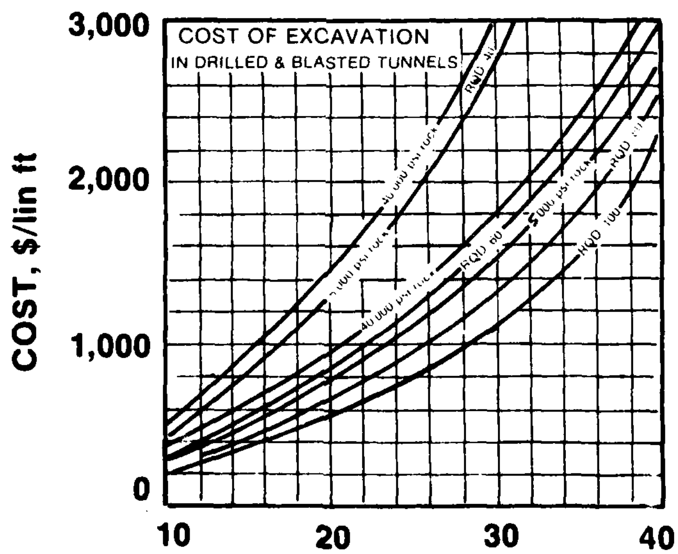


Figure 50. Width or Height, B(ft). Cost of Excavation in Drilled & Blasted Tunnels

If the tunnel operation is in a wet heading, the additional cost is found from Figure 51. In addition to the direct costs of collection and disposal of water, the curves in Figure 51 include all the indirect additional costs of excavation, mucking, and supports caused by the presence of inflowing water.

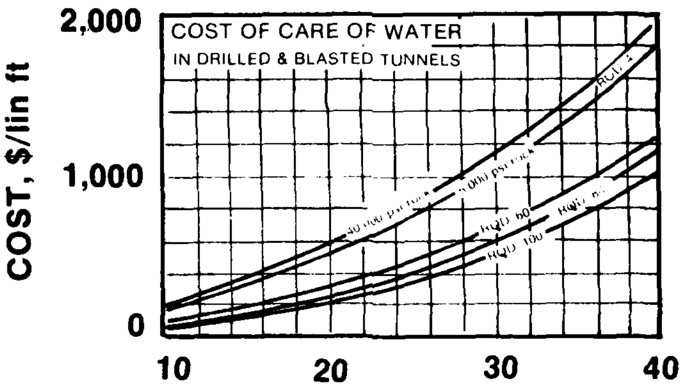
If the tunnel is to be lined, the additional cost is found by entering Figure 52 with the finished opening size of the tunnel. The costs from Figure 52 include costs of additional excavation, mucking, and supports required for the increased size of the opening to provide space for the lining to be constructed. It is unnecessary to enter Figure 50 with the actual excavated size for a lined tunnel; enter both Figures 50 and 52 with the finished size (and Figure 51, if applicable).

All of the costs from Figures 50, 51, and 52 are additive. For example, to find the cost of a 5,000-ft long (1,520 m), 20-ft-wide (6 m) lined tunnel in a wet heading, driven through rock with RQD 60 and strength of 20,000 psi (140,000 kN/m^2), all of the curves should be entered at the nominal finished size of 20 ft (6 m). The resulting cost of the tunnel is:

Excavation		\$ 900/ft (\$2,900/m)
Water		\$ 300/ft (\$ 980/m)
Lining		\$ 720/ft (\$2,300/m)
	TOTAL	\$1,920/ft x 5,000 = \$9,600,000 (\$6,300/m x 1,520 = \$9,600,000)

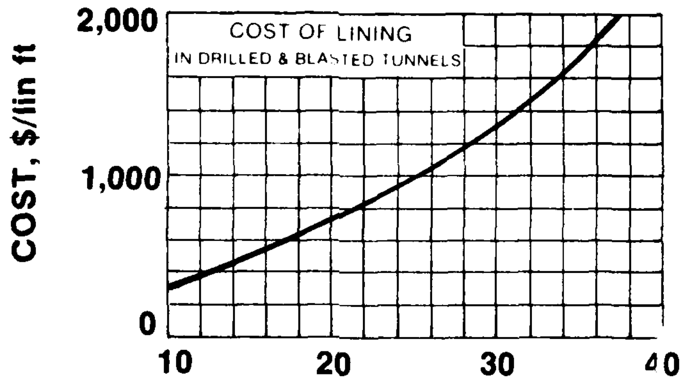
The above computations for D & B tunnels generally apply to machine-bored tunnels. The presentation of the cost data is necessarily more elaborate for machine-bored tunnels because of the greater sensitivity to rock strength by machine than by drilling and blasting.

For comparison of estimated costs of drilling and blasting versus machine tunneling, care must be taken in blind usage of the cost curves



WIDTH OR HEIGHT, B(ft)

FIGURE 51 - Cost of Care of Water in Drilled and Blasted Tunnels



WIDTH OR HEIGHT, B(ft)

FIGURE 52 - Cost of Lining in Drilled and Blasted Tunnels

which might lead to erroneous conclusions. The character of the surface of a machine-bored tunnel is quite different from that of a drilled and blasted tunnel. The machine-bored surface usually will be smooth and adjustments made accordingly.

Also, the total time required for mobilization and construction for a machine-bored tunnel may be considerably greater than for a drilled and blasted tunnel. Shortening the construction time would require the mobilization of additional crews and equipment, which is relatively much more costly for a machine-bored than for a drilled and blasted tunnel. The average time required for fabrication and mobilization of a tunnel-boring machine is on the order of 9 to 12 months, but this is expected to decrease as a larger number of used machines becomes available.

The technology of machine tunneling is currently advancing at a faster rate than that of drilling and blasting, and is therefore, likely to experience a slower rate of cost escalation. Whereas it was once universally agreed that tunnel-boring machines were much more sensitive to changing geologic conditions than was drilling and blasting construction, there is now a contention by some tunnel boring machine manufacturers that the reverse is true today. Whether this contention is entirely true does not alter the fact that a great deal of research is going into machine tunneling.

The costs for machine-bored tunnels were generated, like those for drilled/blasted tunnels, by entering a large number (192) of input data sets, those for machine-bored tunnels being generally the same as for drilled and blasted tunnels except that the shape was changed to circular.

As for drilled and blasted tunnels, the basic tunneling costs from Figures 53-56 include the costs of all the usual machine-drilled construction operations in a dry, unlined heading: excavation, mucking, supports, and ventilation.

The additional costs of tunneling are incurred in a wet heading (Figures 57-60) and the tunnel is to be lined (Figure 61). In the case of a lined tunnel, Figures 53-56 and 57-60 should be entered with the finished diameter, as the additional incremental cost of driving the larger excavated diameter required to accommodate the lining is included in the costs in Figure 61.

The costs from Figures 53-56, 57-60, and 61 are additive. For example, to find the cost of a 5,000-ft long (1,520 m), 20-ft-diameter (6 m) tunnel in a wet heading, driven through rock with RQD 6 and strength of 20,000 psi (140,000 kN/m^2), entering the curves at the finished diameter of 20 ft (6 m) yields the following costs:

Excavation		\$ 860/ft (\$2,800/m)
Water		\$ 380/ft (\$1,200/m)
Lining		\$ 380/ft (\$1,200/m)
	TOTAL	\$1,620/ft x 5,000 = \$8,100,000 (\$5,320/m x 1,520 = \$8,100,000)

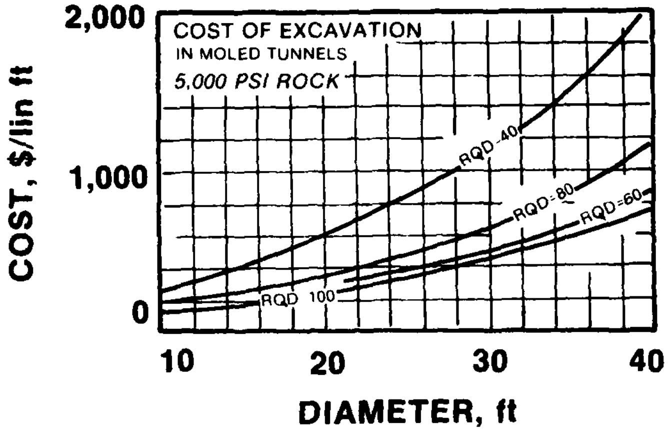


FIGURE 53 - Cost of Excavation in Moled Tunnels
5,000 psi Rock

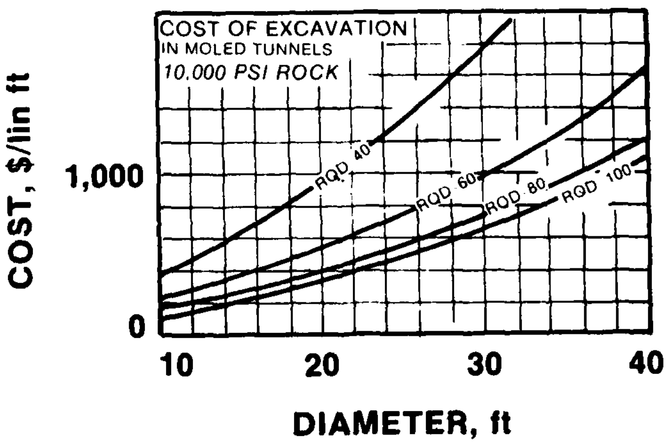


FIGURE 54 - Cost of Excavation in Moled Tunnels
10,000 psi Rock

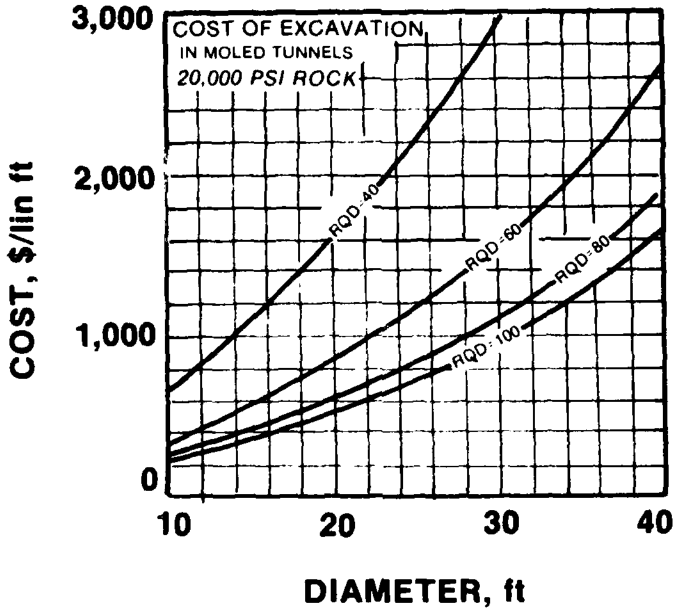


FIGURE 55 - Cost of Excavation in Moled Tunnels
20,000 psi Rock

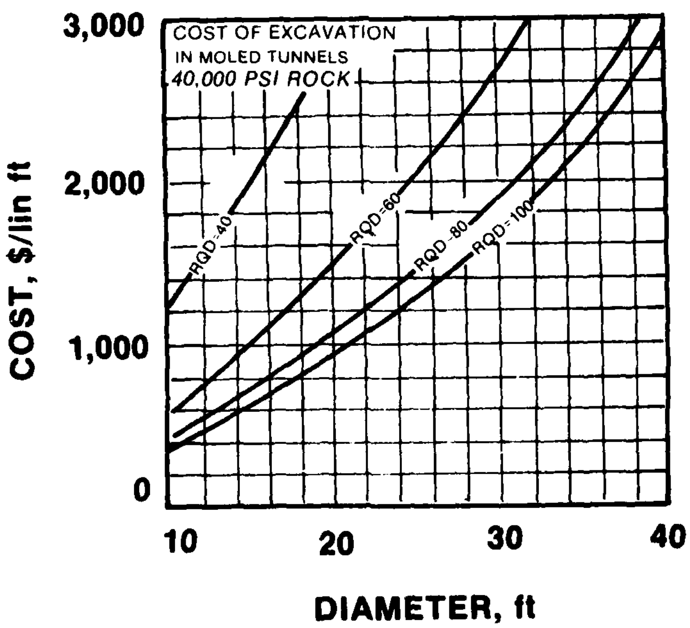


FIGURE 56 - Cost of Excavation in Moled Tunnels
40,000 psi Rock

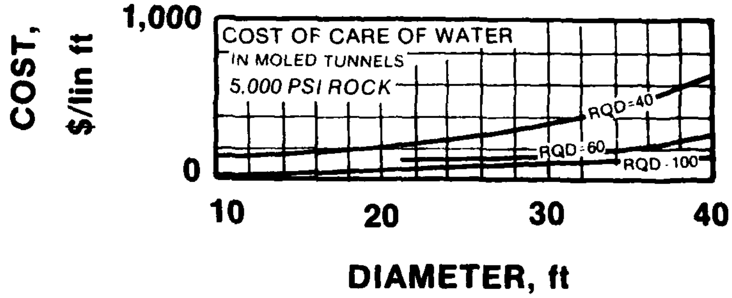


FIGURE 57 - Cost of Care of Water in Moled Tunnels
5,000 psi Rock

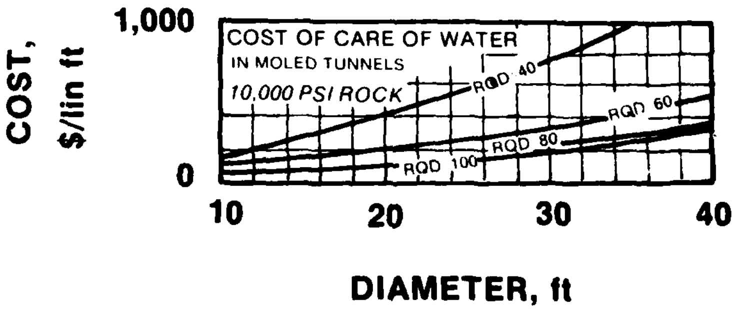


FIGURE 58 - Cost of Care of Water in Moled Tunnels
10,000 psi Rock

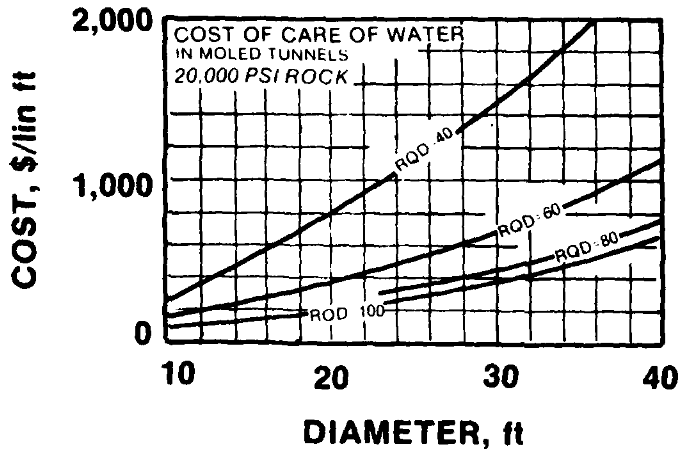


FIGURE 59 - Cost of Care of Water in Moled Tunnels
20,000 psi Rock

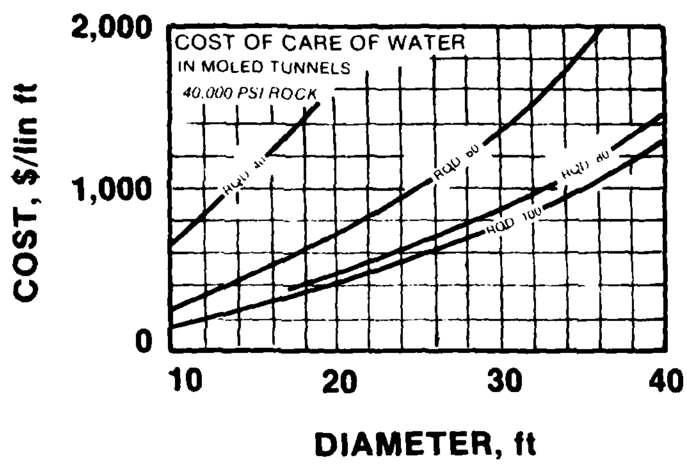


FIGURE 60 - Cost of Care of Water in Moled Tunnels
40,000 psi Rock

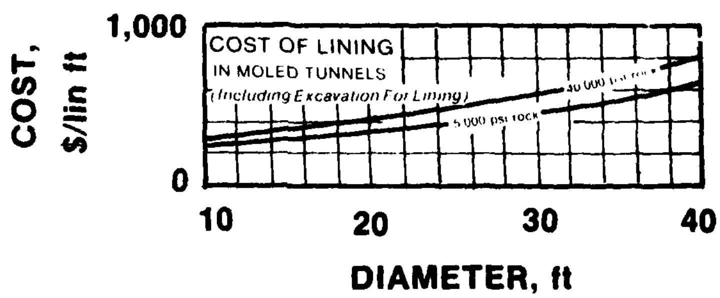


FIGURE 61 - Cost of Lining in Moled Tunnels
(Including Excavation for Lining)

GENERAL OPERATIONAL PROBLEMS

A recent report by Mayo, et al (Ref. 16), examined the tunneling industry in the United States with respect to demand for services, the make-up of the industry, and the history of its problems and prospects. Also included in the report are lists of owners, engineer firms, tunnel builders, and specialized suppliers. An analysis is made of how business is obtained, estimates prepared and projects conducted, as well as factors in decision making and risk management. A review is included of manpower, research and development needs for all types of tunnels with emphasis on rapid transit.

It is noted that recent tunneling experience has been "disastrous" because of price escalation, delays and disruptions, litigation, and erosion of political support.

The following general subjects are analyzed: background, how the industry works, types and characteristics of industry participants, and management problems: risks and resources. More specific subjects are treated, such as the demand for tunneling, tunnel engineering, contracting firms, capacity of the industry, supplier support, bonding, school sources of tunnel engineers, and safety and research.

One of the greatest needs in research continues to be for prediction of geology along the bore of the tunnel. The best methods are still detailed geologic mapping and diamond drilling.

All of the details of Reference 16 are pertinent to the proposed feasibility study. The conclusions and recommendations are summarized as follows:

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16. Mayo, R.S., J.E. Barrett, and R.J. Jenng, June 1976, "Tunneling, the State of the Industry," Crestrusin Co. (PB-256, 817).

A new viewpoint on the tunneling industry's problems and opportunities, coupled with specific technical studies, can lead to improved policy for the industry. Factors which influence capacity and risk-taking have been identified, including operating and financial relationships not readily visible. These range from financing arrangements by owners to decision making at various levels of multi-industry companies. The main objective of the analysis was the reduction of costs so that underground construction can remain an acceptable option for transportation planners.

The promising areas for cost reduction are given as: innovation in design, innovation in materials and equipment, avoidance of supply shortages, sharing of risk through contractual practices, improvement of operational efficiency, and measurement of productivity.

The actions urged for industry are the use of new incentives for progress in the industry and the following recommendations to the U.S. Department of Transportation and the tunneling industry, reproduced here with minor changes.

INNOVATION IN DESIGN. In U.S. transportation tunneling, a system has evolved which strongly discourages innovations or changes in practices or design, and little improvement in productivity will occur until two major related issues are addressed.

- Where combinations of organizations are involved in managerial decisions, such as establishing design criteria and practice, a system of accountability for decisions must be established.

- With accountability, a better risk sharing system is needed. This should encompass decisions made by the owner's staff, engineering consultants, and construction contractors.

These issues are critical for achieving healthy levels of innovation and productivity in transportation tunneling. Other types of publicly funded underground construction have experienced owner-staffs who make

decisions involving design and practice through a review process. Thus, risk is accepted by the owner through a process of accountability for decisions resulting from effective reviews, which is totally missing in the U.S. transportation tunneling industry. In the U.S. industry, the owner generally relies on a consultant to make major decisions for criteria and practice, which raises these questions:

- WHAT INCENTIVE DOES THE ENGINEERING CONSULTANT HAVE TO RECOMMEND COST EFFECTIVE CHANGES IF THE INDUSTRY MUST ACCEPT TOTALLY THE RISK, HOWEVER SMALL, FOR THESE CHANGES?

Under these circumstances, use of traditional design is the most prudent course. The consultant has nothing to gain from accepting the risk attached to any change.

- WHAT INCENTIVE LIES WITH THE OWNER TO APPROVE COST EFFECTIVE CHANGES, IF THE RESPONSIBILITY FOR THIS DECISION RESTS WITH ONE INDIVIDUAL OR ONE GROUP, AND THERE IS NO PAYOFF FOR INNOVATION?

Currently, the owner must exercise judgment based on the potential gains or losses from a new design. If a risk decision is accepted and implemented successfully, the manager is, by definition, exercising proper judgment. However, if the risk is accepted and the results are bad, then the manager has failed, even if the correct decision was made.

Without altering the organization structure of the industry, these questions can be dealt with by providing a "third party" review system. Critical requirements for such a review system are:

1. Third party means that members of a review group may not have vested interests with the owners (be it the federal government or a local authority) or the contractor.

2. Reviews must b conducted by people well versed in the technology and accepted as peers.

3. The review process entails no authority other than to ask for rational explanations for major criteria or practice decisions. Reviewers would then declare that the decisions are prudent and represent a proper exercise of judgment, or publicly disagree with them.

If the industry cannot successfully implement this approach, then federal officials may attempt to establish a *group to monitor cost effectiveness*. Most bureaucratic interventions occur after a prolonged period when the industry involved is urged to solve its own problems. Industry members, who generally agree with the above findings, cannot expect the responsible federal money allocators to countenance the present problems indefinitely.

INNOVATION IN MATERIALS AND EQUIPMENT. The tunneling industry has experienced a slow rate of technological innovation, even though the federal government has funded a great deal of research and development on equipment and materials. Little of this research has led to results that are used in the industry.

One suggested problem in guidance and evaluation of federal R&D is that no consensus exists as to the products which will be needed in the future. It is recommended that the federal government develop knowledge of such needs to identify areas with high potential payoff and establish priorities.

MINIMIZING SHORTAGES. The demand statistics show that development of the BART and WMATA projects occurred at a time of high demand for water and sewer tunnels, and this created severe demand peaks. These peaks triggered price escalation because of bidding practices, shortages of key personnel, and shortages in materials and equipment.

Peak shortages were aggravated by procedures in planning and scheduling at the federal level. Contractors competed among themselves, since

there was no mechanism for assessing overall demand or coordinating long-range plans. Some owners were encouraged to construct entire systems in a brief period of time. Both of these practices fostered excessive demand and high prices. Recommended scheduling by the federal government of periodic meetings of key agency people to coordinate but not control the federally funded demand for tunneling.

SHARING OF CONSTRUCTION RISK THROUGH CONTRACTUAL PRACTICES. Risk affects pricing, as shown on the report. Even though firms are willing to accept the technical and legal risks associated with specific jobs, the consumter (taxpayer) pays for this burden. While risk is unavoidable in this type of construction, procedures for handling it are costly at present. Owners, who can spread the risk over a number of jobs, can absorb a larger share of it than construction contractors, many of whom stake their survival on a small number of jobs.

It is recommended that such risk-sharing devices as subsurface contingency clauses, disclosure of fuller geological information, and owner supplied key materials be employed. Thus, the sharing of risk through such contractual devices will reduce the present adversary climate and accompanying high costs of tunneling.

IMPROVEMENT OF OPERATIONAL EFFICIENCY. The role of the engineer in a construction contracting firm is becoming more difficult as jobs become larger, nontechnical problems multiply, and management responsibilities become more formalized. The skills of experienced engineer-executives are critical to the industry in that they must accomplish the jobs at a reasonable cost, incorporate new technology in equipment, materials, and managerial techniques, and sell tunnel jobs to their firms in competition with other types of investment. It is imperative that the industry provide sufficient training for the future engineering executives. The overwhelming

view, in discussions with contractors, was that graduate programs, except for a handful, are of little value to the rising professional engineer in the industry as now constituted.

It is recommended that the universities recognize the growing need for broadly based engineering management training. Their programs should be closely tied to industry needs in technical and financial management and be supplemented by specialized technical seminars. Construction firms should support these efforts by participating in classroom and seminar presentations.

MEASUREMENT OF PRODUCTIVITY. Increased productivity and innovation must be susceptible to verification or measurement. If this cannot be done, then accountability is impossible. At present, almost no meaningful compilation data exist for the tunneling industry. At a detailed technical level, it is all but impossible to compare the results of most technical reports, since the research is not grounded in a consistent theoretical production framework and common measures of outputs and inputs are not used.

It is recommended that the U.S. Department of Transportation initiate the development of a consistent methodology for the measurement of productivity in tunneling. This study should consider analysis of the theoretical framework and empirical data.

MANAGEMENT OF R&D EFFORTS. Research and development that is federally funded and directed should be performed by industry and the universities, as well as the government itself. It should also include incentives, operating experiments, and matching or participation arrangements of a multigroup nature. The management, commercial, and institutional problems of the industry are larger than its technological problems. Research should actively involve owners, engineers, and contractors, and it will then be more likely to lead to realistic, cost-effective results.

The above conclusions of Mayo, er al (Ref. 16), furnish a broad description of the needs of the tunneling industry, some items of which are controversial. For example, the contractual requirements for tunnel projects usually prohibit coincident research in the tunnel, and the risks involved do not permit the implementation of new ideas.

One of the basic recommendations for the tunneling phase for the DBM will be that one or more sections of tunnels be allocated for experimentation as the tunnel is being excavated.